IRON AND STEEL.

THE

ELASTICITY, EXTENSIBILITY, AND TENSILE STRENGTH

OF

IRON AND STEEL.

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TRANSLATED FROM THE SWEDISH, WITH AN ORIGINAL APPENDIX,

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WITH A PREFACE BY JOHN PERCY, M.D., F.R.S.

WITH NINE LITHOGRAPHIC PLATES.

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PREFACE.

THERE is no subject of greater importance to Civil and Mechanical Engineers than the properties of Iron and Steel, which fit them for application to useful purposes; and there is no subject of the kind which more deeply concerns the general public. The lives of the many thousand daily travellers by railway are in no inconsiderable degree at the mercy, so to speak, of Iron and Steel; and the same may also be said of voyagers in ships made of those materials. Architects, moreover, have in recent years largely employed Iron both in private houses and in public buildings; and upon the strength of the girders and columns introduced, the safety of the inmates depends.

Notwithstanding the numerous experimental investigations, which have been conducted in this and other countries, concerning the tensile strength of Iron and Steel, including Cast Iron, much yet remains to be done in that direction. Such problems, for example, as the relation between tensile strength an composition, previous mechanical treatment, and temperature, are at present but very imperfectly solved. Yet, obviously, they are problems of the highest practical value. It is certain that the mechanical properties of a metal may be affected by contamination with certain foreign matters in some cases when present only in extremely minute proportion. All Iron and Steel, manufactured as articles of commerce, contain invariably more or less foreign matter, usually sulphur or phosphorus or both. The carbon in Steel or Cast Iron is not to be regarded as foreign matter, as it

is essential to the existence of Steel and Cast Iron; nor should it be so regarded when existing in small quantity in Malleable Iron.

All workers in metals know how strikingly the properties of malleability, ductility, and hardness are influenced by previous mechanical treatment, such as hammering, rolling, or wire-drawing; and the properties of elasticity as well as tensile strength are also affected by the same cause.

The tensile strength of a metal, it has been well established, varies notably with temperatures between such extremes as occur in habitable climates. A few years ago numerous accidents from breakage of Iron happened on railways in England, during the prevalence of a severe frost, and it was concluded that they were due to the diminished tensile strength of Iron at low temperatures.

Although information, on these problems, may be found scattered through various books and scientific journals, yet they have not hitherto been so systematically investigated as by the Author of this Treatise, M. Styffe, who has devoted some years of patient labour in attempting their solution; and by a life-long training in experimental science, no man could be named better qualified for the task. M. Styffe is Director of the Technological Institution at Stockholm, and I had the pleasure of becoming personally acquainted with him as a colleague on the Jury for Mining and Metallurgical Products of the International Exhibition, 1862. From the high position, which, I know, he occupies in the estimation of scientific men in Sweden, a country which has done so much towards the advancement of every branch of science in Europe, perfect confidence may be placed in the accuracy of his results, though his conclusions may not in every case be accepted.

A detailed account is given of the apparatus employed in determining tensile strength at common and other temperatures, and of the mode of conducting the experiments. The

results are recorded in tables, and for the convenience of the reader the general conclusions are clearly and succinctly stated. The investigation was undertaken by a Commission appointed by His Majesty the King of Sweden, chiefly with the view of determining the relative values of different kinds of Iron and Steel applicable to railway purposes. Of that Commission the Author was a member, and to him was entrusted the carrying out of the necessary experiments. Amongst the numerous samples examined were some, it is alleged, from certain districts in England, which undoubtedly do not represent even the average quality of the Iron there manufactured.

The observations on the "Influence of Phosphorus and Slag on Iron" deserve careful consideration; and a novel doctrine is propounded as to the beneficial influence of the diffusion of slag, through Iron containing phosphorus in sensible quantity, in order to counteract its injurious effect. With regard to the influence of phosphorus in certain proportions upon the tenacity of Iron, the results of the Author agree pretty closely with those of Karsten. The tensile strength of Iron, the Author asserts, is not sensibly impaired by the presence even of 0·2 or 0·3 per cent. of phosphorus, provided the metal has not been strongly heated, after having undergone the operation of rolling or extension by other manipulation. But, what is important, the facility of extension, or, as it is termed, the extensibility of Iron is lessened by phosphorus. It is maintained that the presence of even a considerable quantity of slag or cinder in Iron impregnated with phosphorus, is beneficial by preventing the largely crystalline structure, which otherwise would result from the presence of that element.

There is a statement to the effect that "of the different brands of English Iron examined, only that from Lowmoor was fit for smiths' work." Now, however well adapted for

smiths' work Lowmoor Iron may be, it is certain that there are other brands of English Iron which are equally good for the purpose; and it is therefore desirable to note that, of this class of Irons, only that of Lowmoor was submitted to trial.

With respect to the cause of frequent fracture of certain articles of Iron in severe cold, the Author advances views, which will certainly be combated by many engineers in this country; and which, indeed, are strongly opposed by the Translator, M. Sandberg, from the results of experiments, on a large scale, which, at his suggestion, have been made and mostly conducted by himself at Stockholm during the winter. The results thus arrived at seem to be of much value, and practically to settle the question against the Author. They will be found recorded *in extenso* in an Appendix by the Translator.

The Author pronounces a decided opinion on the injurious influence of phosphorus on Steel, and few men in Europe are entitled, from long and accurate observation, to speak with greater authority on the subject. The Author says he "knows no authenticated instance in which the proportion of phosphorus has been higher than 0·04 per cent. in what has been considered a good Steel." Yet it is only fair to add his opinion, that "with regard to the influence of phosphorus on Steel, our knowledge is at present more imperfect than it is with reference to the effect of that element on Iron."

This volume, though of comparatively small dimensions, contains a copious store of facts established by careful and, I venture to assert, trustworthy experiments. It is satisfactory that its translation into English should have been confided to a Swede,—my friend Mr. C. P. Sandberg,—who has resided many years in England, who was educated as a metallurgist in Sweden, and who has had great experience in all that relates to the manufacture of Iron and Steel, especially in that of rails and railway materials.

The volume is illustrated with numerous working drawings and tables, and amongst the latter are some which particularly merit careful study. I allude to those in which the connection between composition and tensile strength is graphically shown; and, assuredly, one of the most striking and interesting is that tabulated by the Translator (Plate IX.), in which the relative values of Iron and Steel are displayed side by side.

JOHN PERCY.

LONDON, *March*, 1869.

Letter from Dr. Fairbairn, F.R.S., to the Translator.

MANCHESTER, *November 18th*, 1868.

DEAR SIR,—I have carefully examined your excellent translation of the experimental researches on the strength of iron and steel, conducted at the instance of the Swedish Government. These experiments are the more valuable as they relate to the manufacture with charcoal and coke, which enables the scientific public of this and other countries to estimate the respective values of a material which is in constant demand for constructive art.

Your experiments upon the effect of temperature on the resisting powers of iron rails to sudden shocks during the summer and winter months of Sweden are interesting. You will perceive that I have made some remarks, so as to compare them with my own experiments "On the tensile strength of wrought iron at various temperatures," as exhibited in a paper published in the 'Transactions of the British Association for the Advancement of Science for 1856.'

I have great pleasure in bearing my testimony to the scientific and practical value of your translation of this important work, and looking to the innumerable uses to which this material is applied, I have no hesitation in recommending it to the perusal of the architectural and engineering public.

I am, Dear Sir,

Yours faithfully,

(Signed) WM. FAIRBAIRN.

C. P. SANDBERG, ESQ.,
Care of the Swedish Consulate, London.

NOTE BY TRANSLATOR.

The expression "absolute strength," constantly occurring in the following pages, is a literal translation of the Swedish *absoluta styrka*, but it means neither more nor less than what English engineers are accustomed to call "tensile strength."

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ON THE

ELASTICITY, EXTENSIBILITY, AND TENSILE STRENGTH OF IRON AND STEEL.

INTRODUCTION.

At the instance of the Committee appointed by His Majesty the King of Sweden for the purpose of examining railway plant of home manufacture, and of determining the fitness of Swedish iron for such materials (of which committee the author was a member), a tolerably extensive series of experiments has been undertaken, within the last few years, for testing the elasticity, extensibility,[1] and absolute strength of different varieties of iron and steel.

As the qualities of iron and steel are dependent, to a great extent, on the treatment which the metal has received whilst undergoing the processes of welding and rolling, it follows that the greater the number of operations through which the finished article has passed, the more difficult does it become to determine whether certain of the qualities which it exhibits are derived from the raw material originally employed, or whether they have been developed by the manipulation to which the metal has been subjected. As these circumstances should not be forgotten in pronouncing an

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[1] By *extensibility* (Swedish *tänjbarhet*) is to be understood, throughout this essay, that property of a body in virtue of which it can assume, by the action of some external mechanical force, a greater or less elongation, which remains after the force producing it has ceased to operate. This property is therefore only a species of that more general property which Lagerhjelm and others call *skufbarhet* (German *Verschiebbarkeit*), and which embraces every kind of permanent change of form, whether resulting from traction, compression, flexion, or torsion.

opinion on a new product manufactured by inexperienced workmen, the Committee (as expressed in their report presented to His Majesty on the 13th February, 1863[2]) considered that an enquiry into the qualities exhibited by different kinds of iron and steel as they occur in the form of rolled or of forged bars, would be of very considerable importance in determining the employment of these materials for different kinds of railway plant; and in certain cases would be more profitable than an examination of the finished objects manufactured of such materials.

These investigations were commenced by Professor Ångström, but as he was compelled at an early period to abandon the task, they were continued for a while by Herr R. Thalén,[3] of the University of Upsala, and by Engineer K. Cronstrand; but since the beginning of the year 1863, they have been conducted either under the author's immediate direction or by the author himself, with the assistance especially of Engineers Cronstrand and P. Lindell. Under these circumstances the Committee has requested the author to give a systematic account of the entire series of investigations on the subject.

[2] *See* 'Jernkontorets Annaler,' 1864, p. 17.

[3] In a memoir presented to the Royal Academy of Sciences of Stockholm, and printed in the Abstracts of their Proceedings for the year 1863, Herr Thalén has given the chief results of the experiments on extension conducted by him. As some of his researches will be here noticed, the author cannot of course avoid the repetition, to a certain extent, of what occurs in that very able memoir.

CHAPTER I.

Experiments on Tension at the Ordinary Temperature.

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1. *Introduction.*

In determining the different elastic properties of iron and steel, it has been found that in general the most instructive point for examination is the behaviour of the material when subjected to tensile strain, for the sample-bars tested are then stretched at all points of every transverse section, not

only in the same manner but also in the same degree; but when they are subjected to other experiments, such as flexion and torsion, the phenomena become more complicated and difficult of interpretation.

2. *Description of the testing machine.*

The machine employed in the experiments on tensile strain was the hydraulic press formerly used by Assessor P. Lagerhjelm, somewhat strengthened and modified. Although this machine in its original form was described in the *Jernkontorets Annaler* for 1826, it is considered desirable for the better illustration of the present memoir, and for the benefit of those readers who have not access to the original paper, that a description should here be given of the apparatus in its present form, as shown in the accompanying engravings. In Pl. I. the entire apparatus for stretching and measuring is represented; fig. 1 showing an elevation, fig. 2, a plan, fig. 3, a longitudinal section of that portion of the apparatus which is employed for stretching, and fig. 4, a transverse section along the line X Y in fig. 2. In these figures, A is the hydraulic press resting on two strong cast-iron supports B B, each having a sectional form nearly resembling an inverted U. These supports are united by two concave cast-iron plates C C, and rest on a pair of oak tables. *a* is the cylinder of the hydraulic press, *b* the piston, *c* the safety-valve on the cylinder, *d* a tap for drawing off the water whenever it is desired to release the strain on the sample-bar; *e* and *f* are two pumps, of which the larger one, *e*, is employed at the commencement of the pumping, and the smaller one, *f*, at the close, so that the tension may be as gradual as possible; *g* is a cross-piece fastened to the piston of the press, and attached by two screw-bolts to another cross-piece, *h*, which has a central perforation to admit the end of the bar under test. The other end of the sample-bar is attached to a similar cross-piece, *i*, which in its turn is fastened by two screw-bolts, *kk*, to the cross-piece *l*;

and this is united by the screw *m* to the hoop *n*, the inner edge of which rests in a prismatic cavity on the short vertical arm of the bent lever D. This lever, which serves to measure the amount of elongation during tension, is moveable about the edge *p* firmly fastened to the press, and carries at the end of its long horizontal arm a hoop, which rests by means of a prismatic edge on the arm of the lever, and carries a hook beneath for suspension of the scale-pan E. When the sample-bar is inserted between the cross-pieces *h* and *i*, the pump is brought into action and the bar is thus stretched until capable of raising the horizontal arm of the lever D, together with the weights in the scale-pan E. When this is effected, and it is considered that the tension has been in play sufficiently long, the cock *d* is opened, and the elasticity of the bar then forces the water from the press, and the balance D falls on its support F. In order to ascertain that the balance D was always pumped to the same height, a small weight was sometimes suspended above in such a way that when touched by the balance a large index was moved, and thus it was seen at a distance that the pumping should cease. Occasionally, when great accuracy was needed, a small scale was fastened to the support F, in which case it was necessary that some one should be stationed at the scale in order to observe the elevation of the balance.

The edge *p*, on which the arm of the bent lever D turned, was placed rather too high, so that the edge of the hoop *n* was situated, in most of the experiments made under the author's direction, about 5 lines higher than the horizontal axis of the piston. This condition, however, so far from causing any inconvenience, was rather an advantage, inasmuch as the cross-pieces, *i* and *l*, together with their screw-bolts, were raised during tension, so that no friction could arise between them and the slides.[1] As the mean distance

[1] Originally these cross-pieces were hollowed concave at the ends, by which they were inserted between the inner edges of the slides BB; but when the cross-pieces were raised by the press, there arose considerable friction, as Lagerhjelm had already observed; and this rendered the measurement of

from the edge of the hoop to the centre of the end of the pump-piston was about 9 feet, the small declination of the sample-bar from the axis of the piston, or the horizontal line, during tension, could not operate disadvantageously on the press; nor, as will hereafter be shown, could it exert any material influence on the measurement of the strain, which was determined by means of the bent lever.

It might be supposed that the lever should have been provided with edges instead of cavities for the reception of the fulcrum p and the edges of the hoop n. In that case, however, the use of the apparatus would have been more inconvenient; and, moreover, it was found by experiment that the edges did not perceptibly vary in position at different times, and that the measurements of the elongation of the sample-bars thus obtained possessed the requisite degree of accuracy.

These measurements are easily determined by calculation.

Let a and b, in fig. 5, Pl. I., represent the lengths of the arms of the bent lever B A C; let p denote the weight, which if applied to the arm a would have the same effect as the lever exerts by its gravity; let q be the weight of the hoop and scale at C, and r that of the weights in the scale-pan; let α be the angle which the sample-bar makes during tension with the horizontal line, in consequence of the position of the edge of the hoop at B above the axis of the press; and let T_r denote the elongation of the sample-bar;

$$\text{Then } (p + q + r)\, a = T_r\, b \cos \alpha.$$

But $\tan \alpha$ is about $\frac{1}{180}$, and therefore $\cos \alpha = 0{\cdot}999985$, or $= 1$ nearly; whence

$$T_r = (p + q + r)\, \frac{a}{b} \ldots (\mathrm{I}).$$

the extending force less trustworthy. The author, therefore, removed the lower jaws, so that when the press began to work, the cross-pieces could move freely.

3. *Determination of the constants of the testing machine, and of the accuracy with which the elongation of the stretched bars is measured.*

In order to determine accurately the values of the quantity p and the ratio $\frac{a}{b}$, and also to ascertain the accuracy with which the elongation of the sample-bars was measured by the apparatus, the author arranged a strong lever, D E F, with two equal arms at right angles, and three acute prismatic steel edges. This was placed between the cast-iron supports, B B (figs. 1 to 4), about midway between the arm A B of the lever and the end G of the piston, and at such a height that the edge D was in the straight line joining B and G, as shown in fig. 5. The edge E rested in a concave pan of tempered steel, supported steadily by an iron hoop. At D was placed a hoop furnished with a tempered steel pan, which in its turn was connected by an iron rod with the cross-piece i (figs. 2 and 4), and, therefore, united also with the arm B. On the edge F a similar hoop was placed for suspension of a scale-pan. If then T denote the elongation in the direction B D arising from the bent lever B A C, and c and d the respective lengths of the arms D E and E F, and g the sum of all the forces acting at F (that is, the moment of the lever D E F divided by d, together with the weight of the hoop, the scale and the weights placed in the pan), then, when the lever B A C is so balanced that A C is horizontal,

$$\mathrm{T}b \cos a = pa \ldots\ldots (\mathrm{II}).$$

$$\text{and, } \mathrm{T}c \cos a = gd,$$

$$\text{whence } \mathrm{T} = g \frac{d}{c \cos a}.$$

As c and d were each only about 0·75 foot, and as a slight error in their measurement was of considerable influence, the bent lever D E F was turned round so that F E became vertical and D E horizontal, and the larger bent lever was

then again balanced. If the total weight then required to be applied at D, in order to establish equilibrium with respect to the larger lever, is denoted by g', we have

$$T = g' \frac{c}{d \cos \alpha},$$

which, compared with the former equation, gives

$$T = \sqrt{gg'} \frac{1}{\cos \alpha}.$$

If the hoop, with the scale-pan and weights, be now suspended at C on the arm A C, and their weights be represented, as before, by q and r, the elongation in B D by T_r, and the total corresponding weight at F by G, then we obtain

$$T_r\, c \cos \alpha = G\, d;$$

and when the smaller lever is turned round as before, and the total weight then required at D is represented by G′, we have

$$T_r\, d \cos \alpha = G'c.$$

$$\text{But, } (p + q + r)\, a = T_r\, b \cos \alpha,$$

$$\text{and equation (II.) gives } pa = Tb \cos \alpha,$$

$$\text{therefore, } (q + r)\, a = (T_r - T)\, b \cos \alpha,$$

$$\text{and, } \frac{a}{b} = \frac{\sqrt{GG'} - \sqrt{gg'}}{q + r}.$$

When this value of $\frac{a}{b}$ is inserted in equation (II.) we also obtain the value of p.

By several experiments, which were varied in such a manner that the greater lever was poised at C by a larger balance placed above, we obtained the following as the most probable values[2]:—

$$p = 97{\cdot}51,\ \frac{a}{b} = 20{\cdot}084.$$

[2] Herr Thalén determined p by weighing the end C in the scale of a balance and obtained the ratio $\frac{a}{b}$ by direct measurement. He thus found $p = 97{\cdot}55$,

As the scale at D, with its hoop, weighed 55·97, formula (I.) becomes

$$T_r = 20{\cdot}084\ (153{\cdot}48 + r).$$

As to the accuracy with which the measurement of the elongation of the sample-bars was determined by the bent lever B A C, it was found, by the use of the smaller lever, previously mentioned, D E F (fig. 5), that when the scale under F was loaded with 3000 lbs., the arm AC of the larger balance always distinctly changed its position by an additional weight of ½ lb. in the scale. Even when the sensibility of the apparatus was diminished, to a slight extent, by the friction of the lever D E F, the errors committed in measuring the tensile force could be but small in comparison with other sources of error.

4. *Manner of inserting the sample-bars in the machine.*

The method of inserting the bars in the press is a point of considerable importance. For this purpose Messrs. Thalén and Ångström, following Lagerhjelm, pointed the ends of the bars and then folded them double, and by means of conical iron wedges, which clasped the ends, fastened them in the holes in the cross-pieces. This method, however, was attended with much inconvenience. In the first place the bars were weakened by having been heated, and this was particularly the case with the hardest puddled steel, of which most of the samples broke at the ends or at the joints of the wedges. To prevent this, Herr Thalén prepared some strong cast-iron clamps, in which he fixed a bar that had

and $\frac{a}{b} = 20{\cdot}018$; which values he employed in the calculation of his results on tension. Although these simple methods could not give results as exact as those obtained by us, the deviation was nevertheless so small that it has not been considered worth while to correct Thalén's results, which are therefore given in Tables I. and II., in the same form as they were communicated by him.

been broken near the place of fastening, in the manner just noticed, and tightly screwed it in its position in order to be broken afresh. The clamps consisted each of two parallel-sided pieces of cast iron, in which were inserted prisms of hard cast-steel furnished with file-teeth. The ends of the bar were fastened between these prisms and seized by the teeth, when the pieces of cast-iron were screwed together by four strong bolts. The use of these clamps was certainly attended with tolerably satisfactory results, but it occasioned so much inconvenience in other respects that Herr Thalén generally fastened his bars by the method first described, and had recourse to the use of clamps only when a bar had been broken near the end, and it was feared that the breaking strain had therefore been estimated too low. Usually the bar was also broken at the other end, and it therefore became necessary to use clamps at both ends in order to break the bar at a point where it had not been weakened by heat, so that its real strength might be determined. With the use of clamps, the breaking weight, according to Thalén, is augmented not more than from 4% to 5% for the bars tested by him from Surahammar in Sweden, but 10% for the puddled steel marked N.P.2, 13% for B.1, and nearly 37% for N.P.1.

On testing Bessemer steel and cast-steel containing one per cent. or more of carbon, the author has found that bars have broken near the ends where they had been heated, with a load 30% less than that which they afterwards bore when, with the use of clamps, they were broken at another point, which had not been affected by the heat during the treatment described below. Moreover, the use of wedges has the further inconvenience of not allowing the bars to be perfectly free after each load; and it may easily happen too that the bar is bent by wedging. When clamps are used, the bar may indeed be released from the cross-pieces, but the heavy clamps can scarcely be supported so evenly that the bar does not become somewhat bent, nor can the clamps be loosened (an operation which, if performed after each load, would be

a source of great inconvenience) without fear of obtaining a slight permanent deflection.

Having experienced the inconvenience of these methods of fastening, the author "upset" or stubbed the bars at the ends, having furnished each with an iron washer having an aperture of greater diameter than that of the bar. One end of the bar was forged into a small head, so that the washer could not be torn from the bar, whilst the other end was furnished with a screw-nut.

When the bars had been too highly heated at stubbing, it was found that fracture rarely occurred at the part where they had been heated, unless they consisted of cold-short iron or hard steel; for the heat, as far as it extended, had increased the diameter of the bar.[3] By this arrangement the bar could readily be set perfectly free, and was thus exposed to no other force tending to produce curvature, beyond its own gravity, the effect of which was certainly disadvantageous to the measurement of the *absolute* length of the free bar, but it was at least always constant.

The author has, however, occasionally bent the bar at one end, and upset it with a washer at the other, as one extremity might then be readily set free, and the bar thus removed from all tension. The most convenient way of setting the bar at liberty is by loosening the nut of the screw *m* (fig. 2) with a suitable key; and if necessary the nuts of the bolts *k k* may also be unscrewed.

Of late the author has nearly always applied nuts at both ends of the bar; and, in order as far as possible to prevent any oblique strain, the bar has been turned on the inner edge, by which it was connected with the cross-pieces.

[3] In testing steel containing 1 or 2% of carbon, as well as very cold short-iron, fracture usually occurred so near the ends that there was reason to fear it was induced by the heating. The author, therefore, cold-hammered some bars of cold-short iron as far as the heat at stubbing had extended, and thus succeeded in so strengthening the ends that fracture did not occur there. In the rupture of hard steel bars, however, the author was usually obliged to employ clamps.

5. *Division of the sample-bars into feet, and measurement of their sectional area.*

Each sample-bar was about six feet long, and was marked by fine transverse divisional lines at about equal distances from the ends, leaving a length of 5 feet in the middle,[4] which was again divided into whole feet. At each of these six divisional marks the dimensions of the bars were taken in two rectangular directions,—the diameters in round bars or the sides in square bars. These measurements were taken by means of a small micrometer-screw ("Palmer's *Blechlehre*"), the threads being about 0·03937 inch apart, and the screw-heads so divided that measurements might be read off to 0·0003937 inch.[5] Notwithstanding this degree of accuracy in the instrument by which the sectional area of the bars was measured, it is yet possible that errors may have arisen to the extent of about 1%, in consequence of the dimensions of the bars—especially forged bars—being sometimes irregular. Moreover, the surface of the bar having been coated with a thin film of scale, the mean area might exceed the area of the section actually broken by more than 1%. The accordance between the different measurements has, however, generally been so close, that probably an error as great as one per cent. has been exceedingly rare.

6. *Measurement of the elongation of the sample-bars by stretching.*

In order to measure the elongation of the sample-bars by stretching, a small finely-graduated scale was attached to

[4] The samples, Nos. 24 and 25, in Table IV., which were of so cold-short an iron that the rolled bars were broken during transport, had each a length of ouly *one* foot between the outer divisions.

[5] In the first 21 bars from Surahammar, which were tested by Herr Ångström, and for which he determined the breaking strain and the elongation on rupture, the area was measured at only 3 places.

The actual size of the threads in the screw was determined by comparison with a well-tested screw in the possession of the Royal Academy of Sciences of Stockholm.

each of the outer marks at the end of the bars, and therefore at a distance of 5 feet from each other. Of these two scales, that which was placed nearer to the hydraulic press, and had only a few divisional marks, is called the *index scale*, and the other the *measuring scale*. In order to fasten these scales to the bars, they were screwed to brass rings surrounding the bar on three sides, and having the lower edges bent outwards. These edges were in their turn embraced by the upturned edges of a brass plate, through which passed a screw; and by pressing the point of the screw on the lines marked on the bar, the scales were steadily fastened in their proper position. The index-scale attached to the bar is shown of natural size in fig. 6, Pl. I., both in plan and in section. The scale was divided into 280 equal parts by a dividing machine constructed by Froment, and belonging to the University of Upsala; each division corresponding, according to Herr Thalén, to 0·2048 millimètre, or 0·06898 Swedish dec. line (or 0·00786 Eng. inch). In strictness, the divisions on the middle of the scale were indeed about 0·0004 millim. shorter than those at the extremity, but the error thus introduced was too slight to need any correction.

The measurement of the elongation of the bar was effected by a large scale of fir-wood (G, figs. 1 & 2, Pl. I.), furnished with microscopes at the ends. To protect it from hygrometric influences, the surface of this scale was saturated with oil. Guides were placed at the ends of the scale below the microscopes, in order to prevent lateral motion when supported by the scales. That guide, which was placed nearest to the hydraulic press, was furnished with a horizontal screw, touching a small plate *a* (fig. 6), which was attached by a hook to the index-scale, and by means of which the measuring-rod could be so adjusted that the hair-cross of the microscope belonging to the index-scale was immediately over its zero.

For vertical adjustment each microscope was furnished with a vertical set screw resting on the scales, by which arrangement it was easy to regulate their distance from the

object-glasses of the microscopes. Moreover, the measuring-rod carried at that end which was nearest to the hydraulic press a brass axle *t* (fig. 2, Pl. I.) moveable about the conical points of two screws *s s*, which worked in the hollowed ends of the axle, and were fastened to a brass fork *r*, moveable about a horizontal axis by means of two similar screws *u*, *u*. These screws were fastened in a pair of metal hoops elevated on a wooden stage, which rested by means of three set screws on a glass-plate placed on a wooden platform, supported by the cast-iron slides of the hydraulic press. The wooden stage was attached to the press by a tolerably strong spiral spring *z*, by which the measuring-rod was always drawn towards the press, so that the screw on the nearest guide was forced to touch the plate *a* on the index-scale (fig. 6), and the measuring-rod was therefore compelled to follow the motion of the scale.[6] By means of the horizontal axles mentioned above, the measuring-rod might be easily elevated and depressed, but was prevented from turning round on its longitudinal axis; and in order that it should not press on the scales, it was suspended from suitable points by two vertical cords running over pulleys above and carrying balance-weights, so that the bar was nearly counterpoised.

In spite of these arrangements, the position of the index-microscope in relation to the index-scale did not remain constant during the experiment, but varied to a small extent when the bar was subjected to traction or otherwise disturbed, and therefore the index-scale had to be applied at each measurement. Two observers were consequently required—one at each instrument.

The microscope over the measuring-scale could travel along the entire length of the rod by means of a micrometer-screw, and the distance between the axes of the microscopes was thus made exactly 5 Sw. feet, the distance being taken by a special iron measure, on which 5 feet were marked.

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[6] The principal arrangement of the measuring instrument above described was due to the first director of these investigations, Professor C. A. Ångström.

During the greater number of the observations, the microscopes employed were those belonging to the Astronomical Observatory of the Royal Academy of Sciences at Stockholm, but latterly use has been made of a pair of microscopes imported from Messrs. Repsold, of Hamburg, for the Royal Technological Institute. All these microscopes, as is now usual with such instruments, were furnished each with two parallel hairs fastened to a micrometer screw, the head of which was divided into 100 or 120 equal parts; by which construction it was possible to read off the position of the parallel hairs to at least 0·0005 millimètre,—a degree of accuracy far exceeding that which is actually necessary. The position of these hairs should be so adjusted that the divisional parts of the scale come between them exactly in the middle; but this operation could not always be effected with an equal degree of accuracy. As, however, the distance between the hairs did not, in any of the microscopes, exceed 0·035 millimètre, or 0·17 of a division on the scale (and in Repsold's instrument was only 0·13 of a division) the errors in adjusting both the microscopes could not amount to more than 0·01 millim., or 0·05 of a division on the scale.[7] This degree of accuracy is quite sufficient for measuring the permanent elongation of the bar, for the amount of this depends to a great extent not only on the manner in which the tension is effected (that is to say, on the greater or less care with which the pumping is performed), but also on the time during which the strain is in operation. When the permanent elongation exceeded a certain limit, a new elongation was obtained

[7] In using Repsold's microscopes the deviation has rarely been more than 0·01 of a division, when the bars have not been in the slightest degree disturbed, and care has been taken to remove all sources of error arising from changes of temperature in the bars and instruments of measurement, as by radiation from gas-flames. In consequence, however, of small variations in the curvature of the bar, and the difficulty of preventing slight changes of temperature in both the bar and the measuring instruments, so great an accordance cannot be generally expected between the measurements of the bar when stretched several times with the same weight. A change of temperature of 0·25° C. occasions a change in the length of the 5-feet bar amounting to 0·02 of a division on the scale.

at almost every stroke of the piston, although the pumping was performed very slowly. Even when the extension is quite uniform, a bar strained beyond a certain limit may—as Hodgkinson has shown—continue to elongate perceptibly after the lapse of several hours, as will hereafter be seen. A greater degree of accuracy is needed only for the determination of the modulus of elasticity.

When the elongation was so considerable that the scale did not suffice to measure it, or when the sample-bar was exceedingly hard or but slightly extensible, so that there was fear of its being broken early, both the scales and the microscopes were removed, and the measurement effected by a paper scale attached to a wooden bar, and divided into decimals of a line.

7. *Experiments on traction; their object, and the different modes in which they have been conducted.*

Some of the experiments on tension were undertaken solely with a view to determine the absolute strength and the extensibility of the sample-bars. In order to determine the latter quality, the elongation of the bar divided into feet was measured after fracture;[8] and also the area of the fracture. In consequence of the irregular form of the fractured surface, it was only possible to measure it with

[8] When the bar broke between the outer marks made on the bar 5 feet apart, Herr Thalén regarded only the elongation of the parts of the original length of one foot, where fracture had not occurred, and the elongations given in Tables I. and II. are calculated in this way. The author on the contrary considered it always necessary to reckon the elongation on the entire length between the outer marks; because the elongation nearest to the place of rupture is in general the greatest, and of course, in all the experiments, enters into the measurement of the permanent elongations. According to the method first mentioned, it occasionally happens that the percentage of elongation *after* rupture is smaller than it is with the loads which immediately *precede* fracture. According to the latter method of calculation the elongations would naturally be somewhat *greater* for the bars given in Tables I. and II., than what is there recorded.

When fracture occurred outside the marks, the bar has always been again broken in order to make the experiments, as far as possible, comparative.

calipers or compasses, and it was therefore impossible to attain the same degree of accuracy as in the measurement of the mean area. Such accuracy was not, however, necessary in this case.

With nearly all the varieties of iron and steel examined, separate experiments—those on elasticity—were undertaken, to determine with what load a permanent elongation is first practically observable, and in what proportion such elongation is increased by augmented loads. With regard to the elastic elongation, or that elongation which disappears when the stretching force is removed, it certainly seems established by the experiments of Wertheim and other observers, that it is at least nearly proportional to the stretching force, and that it does not materially differ in iron and steel, or in different kinds of these metals. As, however, these statements stand opposed to those of the earlier authorities—such as Redtenbacher, Morin, Reuleaux, and others—the author, by means of the apparatus previously employed, determined as accurately as possible the modulus of elasticity for certain kinds of iron and steel.

When Herr Thalén commenced his experiments, he laid especial stress on the determination of the limit of elasticity in different sorts of iron and steel, using that term as defined by Wertheim[9] and others; that is to say, on the determination of the load by which a bar attains a permanent elongation equivalent to 0·00005 of its original length. But as he soon perceived how difficult it was to determine exactly the limit of elasticity as thus defined, and to base upon it any comparison between different makes of iron and steel, he represented by means of curves, the permanent elongations of the bar by additional loads, and sought to determine, as nearly as possible, their points of maximum curvature. The *ordinates* to these curves represent the load expressed in lbs. per square line, whilst the *abscissæ* represent the permanent elongations of the bar; and the scale was such that 10 lines[10]

[9] Poggendorff's 'Annalen, Ergänzungs-Band II.'

[10] 1 English inch = 8·6 Swedish lines.

in height corresponded to a load of 100 lbs. per square line, and 10 lines in the direction of length to an elongation in the 5-feet sample-bar of 10 divisions on the scale, which again was equivalent to an elongation of 0·138 line per foot. Considerable attention was also paid to the permanent elongation which corresponds to the neighbourhood of the maximum curvature in curves of similar construction; but, for reasons which will be afterwards given, it has not been considered right to take this curvature as a *measure* of the stiffness of the bar; and the author has accordingly given another definition of the limit of elasticity.

In examining the elasticity of a metal, the loads have always been so small at the commencement of an experiment that they have not occasioned any perceptible permanent elongation, and they have in general been afterwards increased by putting into the scale attached to the balance a weight of from 10 to 20 lbs. each time. After the addition of each weight, the permanent elongation thereby occasioned has been measured. When a bar approached its limit of elasticity (using that term in the sense afterwards explained), or when the load has been so great that it was presumed the bar would soon break, the successive additions to the load have been less than usual, in order to determine with greater accuracy the position of the limit of elasticity and the absolute strength of the material.

As the experiments of Wertheim and Hodgkinson have shown that the length of *time* during which the straining force is allowed to operate exerts considerable influence, both on the amount of permanent elongation—especially when that has already been considerable—and on the load at which fracture occurs, we have always taken care to allow the straining force to operate for nearly equal times, so that the different experiments might admit of comparison one with another. When the balance has been raised to the fixed mark and has nearly settled, it has been allowed to remain at rest for one or two minutes, according to the amount by which the load has been increased. It has generally been

considered unnecessary to keep the straining force in action much longer, and indeed with the apparatus employed it would have been difficult to do so when a great weight was acting, for it was impossible to keep the packing round the piston of the press so tight as to prevent leakage. It was not found possible to determine precisely the time during which the force was in operation, because the press begins to stretch the bar before the balance is raised from its support. This is especially the case in experiments on highly extensible bars, as these suffer elongation long before the balance is elevated.

The bars were not always set quite free after each additional load, but were usually measured whilst strained by a suitable weight, consisting of the balance either alone, or with the scale-pan, or with the attached weight. This stretching weight has not, however, been sufficiently powerful to produce any perceptible permanent elongation, but has only served to keep the bar as straight as possible whilst under tension. But when the author commenced to use washers and nuts at the ends of the sample-bars for fastening them to the cross-pieces of the apparatus, or when washers were used at one end and wedges at the other, the bar, if stretched by a great load so that the removal of the weights would have been too troublesome, was usually set free after each load, in order to measure the permanent elongation arising therefrom; the bar being relaxed by loosening the nut of the screw *m* (fig. 2) in the manner previously described.

When the bar is thus perfectly free, its absolute length cannot be measured with any great degree of accuracy; for, being supported only at the ends, even if originally straight, it becomes bent by its own weight. The length obtained by measurement is yet less than the actual length, as will afterwards be shown, because the scales by which the measurement is taken are not placed exactly in the middle line of the bar, but are rather above its upper surface. If, however, the bar were neither bent nor straightened by tension, the difference of the two measurements of the free bar, be-

tween which the bar had stretched, would correctly indicate the permanent elongation occasioned by the tension, because the effect of weight in bending the bar is always the same, and the results generally show a close agreement. Certain bars, however, by stretching, especially with great loads, have been deflected to an extent which in the middle of the bar has occasionally amounted to several lines. In some cases this curvature may have arisen from the method of fastening the bar, being such that the stretching force has not acted centrally. We are, however, convinced that this was not always the cause of the curvature; for bars which have been considerably bent during tension have afterwards been purposely fastened in the apparatus in such a way that they ought to have been bent in the opposite direction; and yet on trial this effect has not followed. The cause, therefore, can only be that the material in the bar was not uniform throughout, or that it had suffered a somewhat different mechanical treatment during rolling or subsequently; the bar having, for example, been straightened when cold. Indeed, the limit of elasticity, as will afterwards be shown, may be so raised by stretching that it shall approach very near the breaking strain; and if, by straightening a bar when cold, the fibres on one side are stretched, and thus attain a higher limit of elasticity than those on the other side,[1] it may happen that the latter on tension suffer a permanent elongation earlier, and that the bar thus assumes a convexity on that side.

8. *Calculation of error in measuring the length, arising from the bar not being perfectly straight.*

In what degree such curves affect the accuracy of measurement of the bars may be approximately calculated by assuming that the curve is an arc of a circle;—an assumption

[1] Wiedeman's Experiments (*Poggendorff's Annalen*, 1859) show that flexion does not raise but rather lowers the limit of elasticity on that side where the fibres are compressed by flexure.

which may generally be accepted when the bars are homogeneous and of regular dimensions, and when the curvature is but slight.

In fig. 3 (Pl. II.) A B C represents the axis of the bar in its own plane, which makes an angle a with the horizon; and fig. 2 shows a vertical transverse section taken through the middle of the bar. The angle a is regarded as positive when the bar is bent downwards, and as negative when bent upwards. In fig. 1, on the contrary, A B C is a projection of the axis in a vertical plane passing through the zero points of the scales, marked D and F. If through each of these points a plane be drawn cutting the axis at right angles in A and C, these planes, as well as their line of intersection G I (fig. 2) must be at right angles to the plane in which the axis lies. Further, if a plane be drawn parallel to the last-mentioned plane through the point D, cutting the line G I in H; then, since D and F must, according to our supposition, lie symmetrically with regard to the axis, this plane must also pass through F; and if, with H as a centre, a circular arc be described through D, this arc will also pass through F. In fig. 3, D E F is the projection of this circular arc on the plane of the axis; and in figs. 1 and 2, D E F and E D are its projections on the planes represented by these figures. The actual length of the arc D E F, as well as that of the arc A B C, is of course seen only in fig. 3; but their true heights E K and B L, with their radii D H and C H, are shown also in fig. 2, where they correspond—the former with E D and A B, and the latter with E H and B I respectively. In the following description the lengths of the arcs A B C and D E F (fig. 3) will be denoted by s and s_1, of B L and E K by h and h_1, of C H and D H by r and r_1, of the chords A C and D F by a and a_1, and the height of the scales above the axis when the bar is straight by b.

As long as the bar is straight, D and F of course lie vertically above A and C, and the distance between D and F, the zero-points of the scales, is also then an exact measure of the length of the axis between A and C; but when the bar

is bent, only the length of D F (figs. 1 and 3), or a_1, is measured, and there is thus an error introduced equal to

$$s - a_1 = (s - s_1) + (s_1 - a_1).$$

When the angles which correspond to the arcs s and s_1, are of the same magnitude,

$$s : s_1 = r : r_1 ;$$

$$\text{whence, } (s - s_1) : s = (r - r_1) : r,$$

$$\text{and } s - s_1 = (r - r_1)\,\frac{s}{r}.$$

But, $r - r_1 = b \sin a$, for EB (fig. 2) equals b, or the height of the scales above the axis; and EB, if the scales are tolerably well adjusted, is always nearly vertical. As also

$$(2\,r - h)\,h = \frac{a^2}{4}, \text{ whence } r = \frac{a^2 + 4h^2}{8h},$$

and as $s^2 = a^2 + 4\,h^2$ approximately, therefore $\frac{s}{r} = \frac{8h}{s}$.

If these values be substituted for $r - r_1$ and $\frac{s}{r}$ in the value of $s - s_1$, then the equation becomes

$$s - s_1 = \frac{8bh \sin a}{s}.$$

When $\quad s_1^2 - a_1^2 = 4h_1^2$ approximately, then also $s_1 - a_1 = \frac{4h_1^2}{s_1 + a_1}$, which may with sufficient exactness be regarded as $= \frac{2h_1^2}{s_1}$, and as $\frac{h_1}{s_1} = \frac{h}{s}$, and $\frac{h_1}{h} = 1$ nearly, then $s_1 - a_1 = \frac{2h^2}{s}$. Thus we obtain $s - a_1 = \frac{8bh \sin a + 2h^2}{s}$.

The surfaces of the scales in the experiments on bars of 4 lines in diameter lay about 3·6 lines above the axis of the sample-bar, and when this value of b is inserted in the formula last given, we finally obtain

$$s - a_1 = 0{\cdot}0576\,h \sin a + 0{\cdot}004\,h^2.$$

As found from this formula, a deflection of only 0·2 line, when $a = 90°$ (that is, when the curvature is downwards in a

vertical plane), gives rise to an error of 0·0117 line, which corresponds to 0·17 of a division of our scale; whilst the error in adjusting the two instruments of measurement ought not to exceed at most 0·05 of a division on the scale.

In those experiments which required a great degree of accuracy, as in the determination of the modulus of elasticity, the author has always taken as a starting-point for his comparisons the length of a bar subject to a certain moderate degree of tension, at which he had ascertained, by previous experiments, that the bar would not obtain any perceptible permanent elongation.

9. *Different kinds of Iron and Steel examined.*

The principal object of these investigations was the determination of the relative values of different kinds of iron and steel applicable to railway purposes; and therefore the examination was directed especially to such varieties as are employed for these purposes, or to those which might be brought into use on a large scale. As the puddled iron from the few Swedish works which produce it, is usually very soft, and as puddled steel has hitherto been manufactured only exceptionally and on a small scale, the Committee, in order to obtain suitable specimens of both puddled iron and puddled steel of different degrees of hardness, proposed to Herr W. Zethelius, the proprietor of the works at Surahammar, that he should expressly prepare for them puddled iron and steel from certain kinds of pig-iron; and to this proposal Herr Zethelius very obligingly acceded. The samples which the Committee obtained from him were puddled from pig-iron prepared at Bispberg, Grangärde, Norberg, Nora Hammarby, Nora Pershytte, and Persberg. They were all No. 2 iron, rolled to round bars of about 4 lines diameter, or square bars of 4 lines in the side. Unfortunately, Zethelius was prevented from puddling as large a quantity of pig-iron as the Committee had desired, and the product obtained from any given brand was thus neces-

sarily affected by the slag produced in the previous working. It is feared, therefore, that the samples cannot be considered as representing, quite characteristically, the particular kind of pig-iron from which each was prepared.

In the accompanying tables these samples of iron and steel are denoted by the initial letters of the pig-iron from which they were manufactured, with the addition, in the case of puddled steel, of the numerals 1, 2, or 3, according as the steel is more or less hard. Thus, for example, N.P.1 signifies the hardest puddled steel from Nora Pershytte pig-iron; N.2 denotes puddled steel of medium hardness from Norberg pig-iron; B-iron refers to puddled iron from Bispberg pig-iron, and so forth.[2]

In addition to these, the following materials have been examined:—

Tilted Bessemer steel and iron from the new works at Högbo, Sandviken, on the Gefle and Dala railway; the steel from a mixture of 45·75 – 50% of Bispberg ore, 27 – 30·5% of Relling ore, and a small proportion of ore from Nyäng, Gösk, Strand, and Erik; and the iron (degree of hardness = 0·3) from 65·5% of Bispberg ore, and 19·25% of Örlaxbo ore, &c.

Rolled Bessemer steel from Carlsdal in Örebro county, manufactured from Persberg and Vicker ores.

Rolled cast-steel, from Wikmanshyttan in Dalecarlia, manufactured from Bispberg ore smelted in crucibles according to Uchatius' method.

Two sorts of cast-steel, tilted under the hammer, from F. Krupp's celebrated steel works at Essen in Westphalia, of which one variety called *middle hard cast-steel*, and marked with a single crown, was, according to the printed prospectus of the manufacturer, adapted for carriage-axles

[2] The experiments on the extension of the samples from Surahammar, at ordinary temperatures, were conducted by Messrs. Thalén, Ångström, and Cronstrand, before the author undertook the direction of these researches; and the results obtained by these gentlemen are given in Tables I. and II. The examination of all other kinds of iron and steel has been performed by the author and his assistants previously mentioned.

and other objects requiring great stiffness and toughness; whilst the other kind, marked with two crowns, was somewhat softer, and was recommended by the manufacturer for the axles of locomotives and marine-engines, piston-rods, &c.

English rolled puddled iron, from Low Moor, a locality renowned for the excellent quality of its iron; the sample branded with the name.

English rolled puddled iron, from Bolckow and Vaughan's works at Middlesbro'-on-Tees; branded "Cleveland," and probably manufactured from Cleveland ore.[3]

English rolled puddled iron, purchased in Stockholm and obtained, according to the merchant, from Dudley in Staffordshire.

Rolled puddled iron from Motala, branded "M.W."; purchased in Stockholm, and therefore (unlike most of the other samples of Swedish iron) not ordered expressly for these experiments.

Rolled iron, once welded, from Åryd in Småland, refined in a French charcoal hearth from pig-iron smelted from lake-ores rich in phosphorus. This iron was obtained for the special purpose of testing a cold-short iron.

Rolled iron, refined in a charcoal hearth, from Hallstahammar in Westmanland: this iron was purchased in Stockholm, and bore the mark "H H" surrounded by a ring.

Rolled iron, refined in an English charcoal hearth, from Lesjöforss in Wermland, Sweden; branded "Ekman and Co."

In addition to the samples mentioned above, others have been obtained, for the sake of comparison, by planing bars out of an English tyre manufactured at the Low Moor Works, and also out of the head and stem of an English rail belonging to the Swedish State railway, and manufactured at Cwm Avon in South Wales: all these bars were rolled out, after welding, to about 4 lines square, or 0·46 Eng. inch.

[3] As the samples of both the Low Moor and the Cleveland iron were procured through an English agent who knew that they were for experimental purposes, it is very probable that they were selected.

10. *Explanation of Tables I. to V., and Plates III. to V.*

Tables I. to V. give the results of experiments on traction performed at ordinary temperatures, or from 50° to 68° Fahrenheit.[4]

To insert details of the observations by which these results have been attained seems to the author quite superfluous, and would, moreover, occupy too large a space. In Table V., however, certain bars have been selected to show the amount of elongation arising from the traction of iron and steel of different degrees of hardness, and to show the greater or less rapidity with which they elongate.

To enable the reader to see these elongations at a glance, some of them are represented graphically by curves; but as these curves do not in general vary to any material extent for iron or steel of the same chemical composition and manufactured in the same way, we have given in Plates III. and IV. only a few examples of such curves chosen from among the different kinds of iron and steel examined. The ordinates represent the amount of the stretching load, expressed in lbs., per square inch, and the abscissæ represent the entire permanent elongation produced by these loads, or by the smaller ones previously employed during the experiments, expressed in percentage form, that is, in lines per foot of the original length of the bar.[5]

In such curves (the form of which is, of course, essentially

[4] To assist in the comparison of these experiments with those performed in other countries, the reader may be reminded that the numbers which express the load in Swedish lbs. per square line (in the original), are by multiplying—

by	4·8201	reduced to	kilogrammes per square centimètre.
„	68·62	„	English pounds per Eng. sq. inch.
„	0·03061	„	„ tons „ sq. inch.
„	65·78	„	German zollpfund per Prussian sq. inch.
„	59·727	„	Vienna pounds per Vienna sq. inch.

[5] In order to show the difference between the Bessemer material and the other, these two plates have been condensed into one (Pl. IX.), where the results of the trials with the Bessemer material are drawn in full, and those with puddled material are dotted. *See the Appendix by the Translator.*

dependent on the proportion between the scales used for the ordinates and abscissæ) the point of maximum curvature demands considerable attention, as Herr Thalén has remarked in his memoir previously cited. If the scale for the elongations be tolerably large, as in Pl. V., where the ratio of the scale of elongation to that of the load is ten times greater than in Pls. III. and IV., this point may be easily determined, as the nearest points of the curves on both sides of the maximum curvature are then tolerably symmetrical and straight, and the position of the point alluded to may be obtained with sufficient accuracy by drawing two tangents to the curves and bisecting the angle between them. This point was thus determined by Herr Thalén for the varieties of iron and steel tested by him from Surahammar, when the curves of elongation were drawn according to the scale used by him. His determination on this point, which differs but little from that of the limit of elasticity to be afterwards explained, is given in Table I.

The position of the maximum curvature is, however, dependent to a certain extent on the scale, according to which the curve of elongation is constructed; and the author has sometimes found a difference of 40 lbs., according as the curve has been constructed on the scale employed in Pls. III. and IV., or on that in Pl. V.[6] For this reason it has not seemed proper to use the maximum curvature of the curve of elongation as a measure of the stiffness, or for the determination of the limit at which any permanent elongation practically begins to be evident.

11. *Limit of elasticity as commonly defined.*

By the "limit of elasticity" is generally meant, as is well known, the least load by which a permanent alteration of

[6] That the position of the maximum curvature is dependent on the scale employed, may be proved mathematically in the following way:—

If $y = f(x)$ be the equation to the curve of elongation, in which y denotes the value of the load in lbs. per square line of the original mean area of the

form is effected; but the determination of this load depends entirely on the delicacy of the instruments used for its measurement. Moreover, we know that an extended bar does not, on removal of the stretching weight, instantaneously resume its original length, but a so-called secondary action (*efterverkan*) ensues; that is to say, the bar at first assumes a length slightly different from its original dimension, and returns only by degrees to its primitive length.

A secondary action of this kind occurs on flexion, and, according to Kupffer,[7] may be observed even after several days; and the same thing doubtless occurs after tension.

12. *Limit of elasticity as defined by Wertheim and others.*

Mindful of the impossibility of determining the position of the limit of elasticity, according to the definition commonly

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bar, and x the corresponding total elongation on a certain scale, then on another scale for the abscissæ, according to which, for the same values of the ordinates, the abscissæ are m times greater, the equation to the curve becomes changed to $y = f\left(\frac{x}{m}\right)$.

If, further, $f'(x)$, $f''(x)$, and $f'''(x)$, denote respectively the first, second, and third derivatives of $f(x)$, we know by the Differential Calculus that the radius of curvature (ρ) to the curve $y = f(x)$ is obtained from the equation $\rho = \pm \dfrac{\left(1 + \overline{f'(x)}^2\right)^{\frac{3}{2}}}{f''(x)}$, and that the values of x, for which ρ is a minimum, or the curve $\dfrac{1}{\rho}$ a maximum, must satisfy the equation $\dfrac{d\rho}{dx} = 0$, that is,

$$f'''(x) \,.\, \left(1 + \overline{f'(x)}^2\right) - 3f'(x) \,.\, \overline{f''(x)}^2 = 0.$$

The value of x, which corresponds to the greatest curvature in the curve $y = f\left(\frac{x}{m}\right)$ must satisfy the equation

$$f'''\left(\frac{x}{m}\right)\left(m^2 + \overline{f'\left(\frac{x}{m}\right)}^2\right) - 3f'\left(\frac{x}{m}\right)\overline{f''\left(\frac{x}{m}\right)}^2 = 0.$$

But if a value x_1 satisfies the former equation, or makes,

$$f'''(x_1)\left(1 + \overline{f'(x_1)}^2\right) - 3f'(x_1)\,\overline{f''(x_1)}^2 = 0,$$

then, for $x = mx$, the latter equation does not generally become $= 0$, but obtains the value $f'''(x_1)(m^2 - 1)$, which cannot be 0, unless either $m = \pm 1$, or $f'''(x_1) = 0$.

[7] 'Recherches expérimentales sur l'élasticité des Métaux.' St. Pétersbourg, 1860.

accepted, Wertheim and several other physicists have defined this limit as that weight which produces a permanent elongation of 0·00005 of the original length. As thus defined, however, the limit is even of less value in comparative experiments on different kinds of iron and steel, for it cannot generally be determined with any degree of accuracy. As received from the iron-works, bars are rarely so true that they can be employed in experiments on tension without having been previously straightened, and this straightening can scarcely ever be performed so accurately that other curves are not produced. From the calculation previously given concerning the effects of curvature on the measurement of the length, it follows that a deflection vertically downwards of 0·43 line in the middle of a bar occasions an error of measurement amounting to about 0·025 line in a 5-feet bar, which is equivalent to 0·00005 of its length. If, therefore, a bar, which when placed in the press has at first a curvature vertically downwards, becomes straightened by tension to such an extent that the deflection is 0·43 line less, the bar has apparently suffered an elongation corresponding to the limit of elasticity as last defined.

But even if we *could* determine when a bar has really suffered an elongation of 0·00005, this would be insufficient information with regard to the stiffness of the metal tested, for an elongation of so insignificant an extent may be produced by very different weights if operating in different ways. Thus, if it can be produced by a certain load stretching the bar for one minute, it may also be produced by a smaller load acting for a longer time, or by several smaller weights which successively stretch the bar; and, indeed, this last condition must always obtain in experiments carried out for determining the limit of elasticity. The position, therefore, of such a limit is dependent, in no small measure, on the method actually employed for its determination. In order to show the approximate position of the limit of elasticity, as defined by Wertheim, some determinations are given in Table I. as obtained by Herr Thalén. The bars tested were

not free when measured, but were strained by a moderate tensile force; and the amount of this stretching weight, which is given in the table, has of course been included in the determination of the limit of elasticity.

13. *New definition of the limit of elasticity.*

As, therefore, no definition of the limit of elasticity yet given[8] has been found perfectly satisfactory, the author ventures to propose a new definition which, in his opinion, possesses considerable advantage over those already in use. If an iron or steel bar be gradually extended by successive loads, which at first are so small that they occasion no perceptible permanent elongation, but are gradually increased, and are always allowed to operate for as many minutes as each additional weight is per cent. of the entire load, then the author regards as the "limit of elasticity" that load by which, when it has been operating by successive small increments as above described, there is produced an increase in the permanent elongation which bears a ratio to the length of the bar equal to 0·01 (or approximates most nearly to 0·01) of the ratio which the increment of weight bears to the total load. Whenever the limit of elasticity is mentioned in the following tables, as well as in those appended, it is always to be understood that the expression is used in accordance with the definition just given, unless the contrary be expressly stated.

It would be inconvenient to increase the load at each separate stretching by an amount less than about 2% of that previously employed; nor indeed is this necessary for the determination of the limit of elasticity, for as long as the

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[8] See Fairbairn's Paper on the Mechanical Properties of Steel, read before the British Association, at Dundee, 1867, for definition of the term "limit of elasticity."—*Remark of the Translator.*

"*Up to the elastic limit the deflections are proportional to their corresponding strains*, but beyond this point the deflections increase in a much higher ratio. Hence the deflection corresponding to the elastic limit is the greatest deflection which is found to follow the elastic law just explained."—*Fairbairn.*

successive additions to the load do not amount to more than a small percentage, it may be assumed, without any considerable error, that these additional weights and the increments in the permanent elongation are proportional. If, therefore, the entire load acting on the bar be represented by P, the additional weight by which the load is each time increased, and which may be constant, by ΔP; the length of the bar by L; the increase in the permanent elongation by ΔL, this increase being produced by the action of $P + \Delta P$, when allowed to operate for $100 \times \frac{\Delta P}{P}$ minutes; then the limit of elasticity, defined as above, corresponds to that load at which $\frac{\Delta L}{L}$ becomes equal, or approaches nearest, to $0{\cdot}01 \frac{\Delta P}{P}$, which may therefore be also expressed as $100 \times \frac{\Delta L}{L} \times \frac{P}{\Delta P} = 1$, or most nearly$=1$.[9] With a little practice it is possible, if the

[9] If the limit of elasticity shall denote a quality that is characteristic for the material tested, and have any practical use, then the value determined for the quantity $\frac{\Delta L}{L} \cdot \frac{P}{\Delta P}$ must be such that this quantity in the neighbourhood of the limit is always increased or diminished when P is increased or diminished, and this so rapidly that it may be determined with sufficient accuracy what value of P gives the value which according to our definition corresponds to the limit of elasticity. Our proposal to distinguish with the name of "limit of elasticity" that value of P which makes $\frac{\Delta L}{L} \cdot \frac{P}{\Delta P} = 0{\cdot}01$, seems to fulfil this condition for iron and steel, as seen by Tab. V., and by the graphic delineations in Plates III. to V.; but sufficiently exact and complete experiments have not yet been undertaken to determine whether it is applicable also to other metals. We naturally desired to give such a definition of the limit of elasticity as should be free from any arbitrary determination, but in this we have not succeeded, as it was not desirable to sacrifice the most important requisition of such a limit, namely, that its position should always be capable of determination with the necessary degree of accuracy. It might be presumed that the limit of elasticity would be placed where, for equal additions to the load, the differences between the successive additions in the permanent elongation attained a maximum; but an examination of the results of experiments on a large number of bars has shown that there are generally several such maxima. Among these, the position of the first was dependent on such small differences in the elongations that they might fairly fall within the limits of errors of observation; and that which was absolutely greatest occurred when the bar obtained a rather considerable elongation, which for iron may amount to 0·5%. Further, the increments of elongation at each extension, as previously

additions to the load be small, to determine with sufficient accuracy the position of the limit of elasticity directly from the record of the experiments, even if that record—as in these researches—merely gives the weights in the scale-pan on the lever connected with the tension-apparatus, and the permanent increments in the length of the 5-feet bar, expressed in divisions of the scale. As before stated, the lever and its scale-pan corresponded to a weight on the scale of 153·48 lbs., and 1 division on the scale=0·06898 line. If now the weight on the scale be denoted by p, the addition to this weight at each successive stretching by Δp, and the corresponding increase in the permanent elongation expressed in divisions of the scale by Δl, then we obtain

$$\frac{100 \cdot \Delta L}{L} \cdot \frac{P}{\Delta P} = 100 \,.\, \Delta l \,.\, \frac{0\cdot06898}{500} \cdot \frac{(153\cdot48 + p)}{\Delta p} \frac{20\cdot084}{20\cdot048},$$

and hence at the limit of elasticity

$$\Delta l \,.\, \frac{(153\cdot48 + p)}{\Delta p} = \text{(or very nearly =) } 72\cdot4.$$

In order, however, to determine the limit of elasticity with greater accuracy, the results of experiments on tension in the neighbourhood of the limit have more often been represented graphically; and for convenience a scale has been used in which 100 lbs. on the scale correspond to 1 dec. inch, and an elongation of 10 divisions on the scale are likewise equal to 1 dec. inch. When the curve of elongation is drawn according to this scale, the tangent to the curve should have at that point which corresponds to the limit of elasticity an inclination towards the axis of abscissæ of $\frac{153\cdot48 + p}{724}$. When, on the contrary, the curve of elongation is drawn on the scale employed in Pl. V., the inclination of the tangent to

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described, are dependent to too great an extent on the method of extension to admit of differences between them being applied to such a determination as is here mentioned.

With regard to very brittle materials, such as hard cast-iron, &c., it is scarcely practicable to determine their limit of elasticity, even if they are capable of assuming a slight permanent elongation previous to fracture.

the axis of abscissæ becomes 0·001 P_1, where P_1 is the load per square line.

In the plate last referred to, fig. 2 shows the commencement of the curve for a soft-iron bar, and fig. 1 that for a steel bar, with which three series of experiments on tension have been performed, and whose limit of elasticity has been gradually raised in the manner afterwards described. Through the points L, B, E, and H, which correspond with the limits of elasticity, and whose ordinates are 490, 685, 835, and 920 [10] respectively, tangents are drawn parallel to each of the lines A N, A O, A P, and A H. As the lines K N, K O, K P, and K H are made equal to the ordinates of the points L, B, E, and H, and as A K is equal to 1000 on the scale of the ordinates, the tangents of the angles which A N, A O, A P, and A H make with the axis of abscissæ were 0·490, 0·685, 0·835, and 0·920 respectively; and these lines have thus the inclination of 0·001 P_1 to the tangents at the limit of elasticity.

The same plate shows also that the limits of elasticity lie very near to, and only a little higher than, the points where the curves of elongation have their maximum curvature; and this is always the case when the curves are described on the scale here employed, or on any other that does not differ widely therefrom. But if the curves be traced on the scale employed in Plates III. and IV., the maximum curvatures will be somewhat higher than the points corresponding with the limits of elasticity; and this is especially marked in the curves for soft-iron.

In order to determine whether greater or less irregularities in the method of applying the tensile force exerted any considerable influence on the accuracy with which the limit of elasticity is determined in the manner previously described, some experiments have been performed with bars which were originally formed of one piece of metal, and should therefore have at least very nearly the same limit of elasticity. These

[10] These numbers represent the load in Swedish lbs. per square line.—*Translator.*

No. of Bar.	Description of Iron or Steel.	Additions to the load at each stretching when nearly reaching the limit of elasticity.	Time during which the loads were on each occasion allowed to operate.	Limit of elasticity, according to Author's new definition.	Limit of elasticity according to Wertheim's definition.
		lbs. per English sq. in.	Minutes.	lbs.	lbs.
1.	Puddled Iron from Motala . . . . Part A	487·2	2	29,575	under 23,742
	,, ,, ... ,, B	992·72	½	29,849	under 22,507
2.	,, ,, ... ,, *a*	960·68	1	26,761	20,586
	,, ,, ... ,, *b*	1461·6	1	26,761	under 21,752
3.	,, Middlesbrough-on-Tees . . ,, A	301·9	2	32,114	28,477
	,, ,, ,, . ,, B	1214·5	1	31,565	under 27,448
4.	,, ,, ,, . ,, *a*	295·06	2	33,486	29,163
	,, ,, ,, . ,, *b*	1200·85	1	35,339	34,310
5.	,, Dudley, ... ,, A	926·37	1	28,271	under 23,536
	,, ,, ... ,, B	940	1	28,447	under 23,948
6.	Cast-Steel (carbon = 1·22%) from Wikmanshyttan, ,, A	1097·92	1	73,100	about 41,172
	,, ,, ,, ,, ,, B	1118·5	1	74,246	about 41,172

were subjected partly to unequal increments in the stretching load, and partly to the same load operating for unequal times. The principal results of these experiments are given in the table opposite.

With the exception of the bar No. 4, the agreement between the values obtained for the limit of elasticity, according to our definition, is as close as need be required. In respect to that bar, No. 4, the difference between the two values must have arisen mainly from some difference in the material forming the two portions; either the metal in the two parts was somewhat different chemically, or one end of the bar had been less heated during rolling than the other. From this, it may be concluded that at each stretching the part *b* obtained a less increase in its permanent elongation than the part *a*, so that when the load on the square inch was raised, for example, from 33,486 lbs. by an addition of 1200 lbs. for the part *b* and 295 lbs. for *a*, the elongation was increased by 0·003% in the former case, and 0·008% in the latter; and consequently even Wertheim's limit of elasticity was about 5147 lbs. per square inch higher for *b* than for *a*. When the limit of elasticity has been raised by tension, as will afterwards be shown, it might possibly be expected that those iron bars which during the experiment have been stretched a greater number of times before reaching their limit of elasticity, or those on which the loads have been operating for a longer space of time, should attain a greater permanent elongation, and consequently have a higher limit of elasticity. As, however, the difference between the permanent elongations has in no case exceeded 0·015%, and as a permanent elongation of from 4% to 6% in the different kinds of iron examined corresponds on the average, as will presently be shown, to an elevation of 6862 lbs. in the limit of elasticity, it will readily be seen that the increase in that limit occasioned by such a difference as that just mentioned (viz., 0·015%) must be far too small to admit of correct determination.

Against our definition of the limit of elasticity, it may certainly be objected that it is to a certain extent arbitrary;

but the same objection may be urged with even greater force against the definition given by Wertheim and other authors. As seen from Table V., the increments in the permanent elongation change rapidly on approaching the limit of elasticity as defined by us; and therefore that limit may be readily determined with sufficient accuracy. Moreover, it is characteristic of the material in the condition to which it has been brought by previous manipulation. Again, its position, as previously shown, is not dependent in any considerable degree on the method employed for its determination, at least within the limits that might reasonably be attained in experiments on tension. At this limit, too, the permanent elongations begin to be so great that they become of practical importance; and in bars which have not been freed from the scale formed during annealing, the limit may be observed by the scale beginning to peel off.

14. *Increase of limit of Elasticity by stretching and other Mechanical Means.*

It is well known that the limit of elasticity in metals may be raised by cold-hammering, cold-rolling, wire-drawing, or by any other manipulation which, acting in the cold, tends to change the relative position of the molecules of the metal. This method of increasing the elasticity is indeed often taken advantage of by workers in metal. We shall afterwards show that the absolute strength may also be augmented by similar mechanical treatment, but that the extensibility is at the same time diminished.

In order to show in what proportion the limit of elasticity is raised by tension, let us refer to fig. 1, Pl. V., where the curve A B C represents the elongation which a sample-bar has obtained by loads amounting to 55,925 lbs. on the square inch; whilst the curves D E F and G H I show the elongations produced when the same bar, after having been stretched ten times by a force of 1029 lbs. per square inch, was again tested with a smaller weight, which was gradually increased to 63,816 lbs. per square inch; and, finally, for the third

time, was submitted to the action of the same force as at the commencement. In these curves all the points determined by observation are marked with a cross. In the curve A B C the limit of elasticity is placed, according to the first experiment, at 47,004 lbs.; according to the second at 57,279 lbs.; and to the third at 63,130 lbs. The limit was thus raised by tension 16,126 lbs.

The same fig. also shows that the upper parts, B C, E F, and H I, lie in the continuation of the direction of each other. By experiments with several other sample-bars of iron and steel, the author is persuaded that the same thing always occurs when a bar is stretched beyond its limit of elasticity, and then submitted to fresh tension, provided that the new series of experiments closely follow the previous ones, and that the temperature during the whole time has not varied to any great extent. If, on the contrary, the bar be allowed to rest awhile before the experiments are renewed, and especially if it be gently heated (for example, to 300° F.) the limit of elasticity is often found to be much higher than might have been expected in consequence of the tension to which it was previously submitted. This subject will, however, be afterwards resumed.

15. *Effect of repeated stretching with the same Load, or with a smaller Load than that previously sustained.*

If a bar be stretched several times in succession by a load sufficiently great to produce a permanent elongation, it is found that this load causes each time a new elongation, although its value, other things being alike, becomes each time less than at the previous experiment, as shown at C in fig. 1, Pl. V., and also seen in Table V., from the results of tension on the bar N.P. 1.[1] Even a smaller load than that which the bar has previously sustained may occasion a permanent elongation; but if the former does not amount to

[1] *Conf.* 'Öfversigten af Vetenskapsakademiens förhandlingar,' 1863, p. 434.

0·9 of the latter, the elongation rarely reaches 0·015%, and for comparatively small loads becomes almost imperceptible; provided, of course, that the tension is exerted in both cases in the same manner.

16. *Investigation of the Curves of Permanent Elongation.*

From the curves which represent the permanent elongations, it is further seen that these elongations are not proportional to the loads employed, but rather to the excess of the loads over that at the limit of elasticity; and that for the same increment of weight they are greater in iron than in steel. Judging from the same curves, iron and soft steel appear to be most sensitive for small increments in the load soon after having passed the limit of elasticity, whence the curves generally show a slight convexity towards the axis of abscissæ.[2] It is easily understood, moreover, that the form of the curve is dependent to a certain extent not merely on the greater or less homogeneousness of the material, and on the treatment to which it has been subjected (especially if hammered), and also on the irregularity of its dimensions, but likewise on the manner in which the tension has been effected. If when the load has reached a certain limit, the additional weight by which it has each time been increased should be diminished, or if the load be allowed to operate for a longer time, the elongation must be somewhat greater, and consequently the inclination of the curve towards the abscissa-axis must be diminished.

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[2] Possibly this sensitiveness may be connected with the development of heat, which always accompanies permanent elongation. A bar of this kind of puddled steel, whose curves show the greatest convexity towards the abscissa-axis, has, when surrounded by water during tension, afforded a curve which nearest to the abscissa-axis is nearly straight (B. 3, Pl. IV.). We have, however, had no opportunity of making any closer investigations on this subject.

17. *Determination of the Absolute Strength and Extensibility.*

To be strictly accurate in the determination of the absolute strength of bars of iron and steel the amount of the breaking weight should be determined on each unit of the original area at the actual place of fracture; but as it is of course impossible to foresee the precise point at which the bar shall break, this area must be always calculated from the areas of the nearest adjacent parts where measurements have been taken. Since, however, it has been found after repeated determinations that this does not differ in any considerable degree from the mean area, the amount of the breaking weight has been calculated in the tables on the square inch of the original mean area. For the same reason the size of the fractured surface has also been compared with that of the original area at that point.

As it may be of interest to know the amount of the load necessary to rupture a bar as compared with that which corresponds to the limit of elasticity, the ratio between these weights is given in a separate column in the tables. This relation, like the absolute strength and the limit of elasticity, is dependent not only on the chemical composition of the bar, but also on the manipulation to which it has been subjected. Thus, for Högbo Bessemer iron treated under the hammer, this ratio is 1·27-1·37; but for a bar of the same kind, which has been heated previously to testing, it becomes 1·81 (see Nos. 9, 10, & 11, Table III.).

As a guide to the determination of extensibility we have, as before stated, measured after rupture the elongation per foot which occurred at fracture, and have also determined the size of the fractured area in relation to the original mean area. In a practical point of view the former is of the greater importance; but if in that case the experiments on tension are to be fully satisfactory, the bar must be as far as possible homogeneous in structure and uniform in dimensions, and must not have been weakened at any point by heating. As evidence of the importance to be attached to this last condi-

tion, it will be sufficient to refer to some of Herr Thalén's experiments. The ends of a bar having been heated and doubled together in order to be fastened in the press, and the bar having been broken near the end in consequence of this heating, it was again introduced into the apparatus and broken by the use of clamps. In this way Thalén found that during the second trial the bar could sometimes assume, without breaking, three times as great an elongation as in the former experiment, although the breaking weight in the latter case was only about 16% greater. In the examination of steel containing about 1·2% of carbon, the author found, by proceeding in the above manner, that the percentage elongation was nearly quadrupled when the breaking weight was raised only about 30%. This arises from the fact that the elongations generally increase more rapidly as the load approaches the breaking weight. With regard to the sample-bars mentioned in Tab. I., which have been broken outside the marks drawn upon them for the sake of measurement, and which it has not been considered necessary to break again with the use of the cast-iron clamps, it is *possible* that the elongations measured may, in consequence of the heating, be somewhat too low. Such bars are therefore indicated in the table by a reference figure referring to a footnote; but there is reason to believe that in most cases the results are sufficiently accurate.

In the course of these investigations it has often been observed that the amount of elongation on fracture is dependent, to a great extent, on the rapidity with which fracture occurs.

The diminution of area at the place of rupture may be taken in general as a tolerably good guide to the determination of extensibility; but the amount of this diminution is also greatly dependent on the homogeneousness of the metal, its freedom from flaws, and the manner in which it has been treated during the experiment. This diminution is by no means proportional to the elongation per foot. Indeed, it may happen that in a given bar the ratio between the area of fracture and the original area shall be greater than in

another bar which has suffered less elongation. The contraction of the fractured surface is, nevertheless, a tolerably accurate measure of the extensibility of any given bar *at the actual place of fracture.* It is, however, as Lagerhjelm has remarked,[3] dependent to some extent on the greater or less rapidity with which fracture has been produced.

18. *Breaking Load on Unit of Area of Fracture.*

As the absolute strength is generally increased, whilst the extensibility is diminished by the presence of a larger proportion of carbon in the material, or by the traction or other mechanical treatment to which it has been subjected, it singularly happens that the breaking load on the unit of the area of fracture is often pretty much the same for good iron as for steel, if they have both been worked by a similar method. The author, therefore, following some foreign writers, has given this load in a separate column in the tables, although he does not consider that it denotes any exact measure of the quality of the material. Thus, a soft-iron bar is not capable of sustaining anything like so great a strain immediately previous to rupture, as it has borne before commencing to contract at the place of fracture. The fractured surface has therefore never sustained the actual breaking strain given in the tables. When bars which contain the same amount of carbon are compared, a small breaking weight on the fractured area denotes, other conditions being similar, an inferior material.[4]

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[3] *See* 'Jernkontorets Annaler,' 1826, Heft II., p. 74.

[4] We have but rarely described the *appearance* of the fractured surface of the bars, partly because this cannot usually be done with sufficient accuracy either by delineation or by description, and partly because the appearance is dependent to a great extent on the manner in which the fracture is produced. When *gradually* broken, the fracture of iron is always fibrous, if the metal is not cold-short, or burnt by long exposure to a welding heat; and the same thing occurs with soft steel. On the other hand, if *suddenly* ruptured, the fractured surface, according to Kirkaldy, is never fibrous. (*Experiments on Wrought-iron and Steel*, Glasgow, 1862, p. 92.)

The appearance of the fracture is, however, always instructive with regard to the freedom of the metal from imperfect welding or from mixed slag.

19. ***Different Effects of annealing and mechanical treatment on the Elasticity, Extensibility, and Absolute Strength of Iron and Steel.***

It is well known that the limit of elasticity, if raised too high by mechanical treatment, can be reduced by the process of annealing. Every one knows, for example, that if iron wire, hard drawn and therefore very stiff, be subjected to annealing, it loses the greater part of its stiffness and becomes soft and flexible. By annealing a bar of iron or steel, we diminish not only the load which corresponds to the limit of elasticity, but also that which is required to produce fracture, whilst on the contrary the extensibility is thus increased; and this effect of annealing is so much the greater, the higher the temperature at which it is performed in relation to that at which the iron or steel has previously been worked. A precisely opposite effect is produced, as already stated, by any mechanical operation which, acting at a low temperature, tends to change the relative position of the molecules of the material; such, for instance, as stretching, cold-hammering, &c. In instituting a comparison between the results obtained for iron and steel of different brands, as given in the annexed tables, the methods of treatment to which they have been exposed, and the different temperatures at which they have been worked, should not be forgotten. In comparing, for example, Bessemer iron from Högbo, which has been hammered (Nos. 9 and 10, Table III.) with the samples from Carlsdal (Nos. 22, 23, and 24, Table III.), which contain the same amount of carbon but have been rolled, it is found that the latter exhibit less strength and stiffness than the former, but thrice the extensibility. In order to clearly determine the effects of different methods of drawing down, the bar No. 23, from Carlsdal, previously broken, was hammered at a low degree of heat (about 570° Fahr.) for a length of about 7 dec. inch, until the sectional area was there diminished to one-half: this portion was then filed even and divided off, and the bar was introduced into the press and broken. At first, it broke with a load of 128,731 lbs. on the square inch,

but it elongated only a little more than 1% (the inch division at which fracture occurred not being included), whilst the area of fracture was 0·74 of the original area. The longer of the two broken parts was then heated to redness and allowed to cool: it was then fastened in the press by the cast-iron clamps previously mentioned, and was again broken. Fracture now occurred with a load of 65,825 lbs. on the square inch of the area which the bar exposed after the previous experiment; and the area of fracture was then only 0·41 of this area. The elongation in a length of 4 inches, including the place of fracture, was 22·7%; whilst at the previous rupture the elongation in the same length, and estimated in the same way, amounted to only 2·7%. A bar of iron from Lesjöforss, made in the English charcoal hearth, after heating and slow cooling, sustained only 44,603 lbs. per square inch; but when its sectional area had been reduced to about one-half by cold hammering, and then smoothed by filing, it could not be broken until the load was increased to 82,892 lbs. per square inch. The elongation, however, then amounted, except at the place of fracture, to not more than 0·5%, although the area of fracture was only 59% of the mean area of the filed part previous to rupture.

20. *Mean Elongation between the limit of Elasticity and Fracture for an increase in the Load of* 6862 *lbs. per Square Inch.*

Whilst the mechanical treatment to which iron and steel have been subjected, and the temperature to which they have been exposed during manufacture, exert a considerable influence not only on the position of the limit of elasticity, and on the absolute strength of the metal, but also on its extensibility; they appear likewise, although in a less degree, to affect that amount of elongation which, reckoned at a mean between the limit of elasticity and fracture, is produced by a certain addition to the load, say of 6862 lbs. per square inch. This elongation is, to a certain extent, characteristic of the chemical quality of the material, as shown by the following results:—

	Per Cent.
Bessemer steel, and so-called Uchatius steel, containing from 1·85 to 1% of carbon	0·3 to 0·9
Puddled steel, carbon 0·7%	1 to 2
Uchatius steel, and other cast-steel, with from 0·69 to 0·61% of carbon	1·2 to 2·1
Bessemer steel and iron, with from 0·42 to 0·33% carbon	1·9 to 4
Cold-short iron from Åryd	0·8 to 3·4
Iron from Dudley containing much slag and phosphorus, and having a sp. grav. of about 7·5	2·5 to 4·2
Puddled iron from Middlesbro'-on-Tees, sp. grav. 7·65	3·4 to 5·9
Puddled iron, more free from slag, from Surahammar (N. & N.P.), and from Low Moor, with sp. gr. of 7·77 to 7·8	6·1 to 9·5
"Lancashire iron" from Lesjöforss, sp. gr. 7·84	7·3 to 7·8

Why the mean elongations of the samples of Bessemer steel, numbered 7 and 8 in Table III., are so small, may probably be explained in the following manner. These bars, like forged steel bars generally, are very unequally stretched; thus, in No. 8, the total elongation on 2 feet was 1·85%, whilst on 1 foot, where fracture occurred, it was 11·5%. Probably the limit of elasticity ascertained, as well as the breaking strain, refers only to that part of the bar last mentioned; and if we calculate the mean elongation of this foot-division corresponding to an increase of 6862 lbs. in the load, it will be found to be 2·13, or nearly the same as that of bar No. 30, which contained the same proportion of carbon but had been rolled. It is evident, however, that if perfect agreement is to be expected between bars of the same chemical composition, they should be homogeneous in structure, and should have undergone precisely similar treatment, whilst their sectional areas should also, of course, be exactly equal. Bars of cast-steel are, no doubt, best adapted for such comparisons, especially those which have been rolled and afterwards filed down with great accuracy.

Experiments on tension have also been carried out with bars (not, however, inserted in the tables) which, before stretching, had been more or less strongly heated to neutralise the effect of the mechanical treatment which the bar had previously undergone. With such bars it was found, as

indeed might have been anticipated, that the elongation, referred to above, was in general somewhat diminished if the heating had been equally strong in all parts of the bar. Sometimes, however, the amount of elongation was augmented; a result which should not have been obtained, if the elongation had been in any essential manner dependent on the mechanical treatment of the material. From the curves in Pls. III. and IV., it is found that the percentage elongation caused by a certain increase in the load, corresponding to the tangent of the angle formed by the inclination of the curve to the axis of ordinates, must be less if the bar has been broken in consequence of any flaw; and it may also be observed within what limits the same elongation may vary according as the fracture is produced more or less readily.

21. *Limit of Elasticity, Absolute Strength, and Extensibility, influenced by Proportion of Carbon.*

On comparing the absolute strength, the position of the limit of elasticity, and the extensibility of different kinds of iron and steel, it is found that the hardest varieties possess the greatest absolute strength, and also require the greatest load before reaching their limit of elasticity, but that they exhibit the least extensibility; whilst, on the contrary, as the hardness is diminished the absolute strength and stiffness are lowered, but the extensibility is increased. Thus, among the samples of iron and steel from Surahammar, it was found that the limit of elasticity in the iron was reached by a weight, on the average, of about 30,789 lbs., and that fracture occurred with 48,720 lbs. on the square inch; but in the hardest steel, or No. 1, the limit of elasticity corresponded to a load of 43,916 lbs., and fracture first occurred with about 87,147 lbs. on the square inch; the mean values being reckoned in all cases. In the steel marked N.P.1, the average absolute strength amounted to 108,419 lbs., and was thus more than twice as high as in puddled iron.

On the contrary, the iron elongated on fracture 2·3 inches

per foot on the average, or nearly 20%; whilst the puddled steel, No. 1, did not stretch much more than 6%, and the hardest and strongest kinds, N.P.1. and B.1., only about 4%.

In order to show more clearly the relation that subsists, in the samples from Surahammar, between the strength of the metal and its proportion of chemically-combined carbon, a small table is here inserted showing the results of experiments on some of the bars. The carbon was determined at the School of Mines, in Fahlun, by Professor Eggertz's colouration test which gives the amount of chemically-combined carbon as near as 0·1%.[5]

Description of iron or steel.	Percentage of Carbon.	Breaking strain in lbs. per square inch of section.
N. P. 1.	0·8	111,781
N. P. 2.	0·7	84,265
B. 1.	0·8	90,921
B. 2.	0·55	86,991
B. 3.	0·5	71,090
B-iron	0·2	48,102
N. H. 1.	0·7	83,441
N. H. 2.	0·7	83,716
P. 1.	0·6	73,492
P. 2.	0·6	82,344
G. 2.	0·5	78,432
G. 2.	0·7	86,049

From the preceding table it is seen that in steel or iron, puddled from the same pig-iron, and worked in the same way and with equal care, the absolute strength increases with the proportion of carbon, provided at least that this does not exceed 0·8%.

In like manner, in Bessemer and Uchatius steel, the

[5] The translator has recently verified the accuracy of this method. On determining, by combustion in oxygen, the amount of carbon in three kinds of Bessemer steel, containing respectively 0·25%, 0·5% and 1%, previously determined by the Eggertz process, he found that in no case did the results obtained by the two methods vary as much as 0·1%.—*Translator.*

absolute strength (as seen in Table III.) is augmented, whilst the extensibility is diminished, by an increase in the proportion of carbon, until it reaches about 1·2%, when the strength is found equal to more than 137,240 lbs. per square inch. But if the amount of carbon be increased to 1·5%, or beyond that amount, then the absolute strength as well as the extensibility is lowered, especially for Bessemer steel.

It would doubtless have been a question of much interest to determine more accurately the condition in which the carbon existed in those bars which were examined; but the author was not in a position to enter upon this investigation, and, indeed, the subject is fraught with such difficulty, in spite of the progress of modern chemistry, that it is questionable whether such researches, if undertaken, would have led to any conclusive results.

22. *Influence of Phosphorus and Slag on Iron.*

Among the varieties of iron examined, those which, after the Lesjöforss iron, contained the smallest proportion of carbon (viz., Cleveland and Åryd irons), but which contained from 0·24% to 0·29% of phosphorus, have been found to possess the greatest absolute strength—Bessemer iron only excepted. It might be supposed that this result is owing to these irons which are rich in phosphorus, having been rolled at a low temperature, when the limit of elasticity is also tolerably high. This, however, is clearly not the principal reason; for certain sample-bars have been heated to redness previously to stretching, and it has then been found that neither the limit of elasticity nor the absolute strength is lower than in other bars of the same make. The strength of a bar of Åryd iron, after exposure to a white heat was first reduced to 47,690 lbs., but the limit of elasticity was still at 38,084 lbs.; and in a bar of Cleveland iron neither the limit of elasticity nor the strength appeared to be in any essential manner diminished by a white heat. (See Nos. 12 and 36, Table IV.)

With regard to the extensibility and other properties dependent on ductility or tenacity, the kinds of iron just referred to exhibited some very important points of difference. Cleveland iron has always shown great extensibility, and even after exposure to a white heat it has been possible to double up cold bars 0·625 inch thick, and join the ends without fracture. But with Åryd iron the mean elongation of three bars on fracture did not amount to more than 6·7%; and a bar which had been raised to a white heat previous to traction elongated only 1%. A cold bar of this iron 0·46 inch thick, could not be bent in a sharper curve than one of about 1·6 inch radius to the axis of the bar. The Cleveland iron, which contained a tolerably large amount of slag and had a specific gravity of about 7·65, always exhibited a distinctly fibrous fracture, with the exception at least of a single bar which had been strongly burnt by long exposure to a white heat; whilst the Åryd iron, on the contrary, was nearly free from slag, had a mean specific gravity of about 7·76, and always broke with a crystalline fracture without any trace of fibre.

The iron from Dudley contained not less than about 0·35% of phosphorus, and so much slag that when an attempt was made to flatten it out, the metal always fractured to a greater or less extent in the direction of its length, and was, therefore, nearly useless for common forgings. This iron certainly showed less absolute strength than the two kinds previously examined; but, with the exception of a single bar, not less strength than several extremely pure and soft kinds of Swedish iron. Although its texture was completely fibrous, it could not, like the Cleveland iron, be doubled cold and folded without fracture. It was, however, much more flexible than the Åryd iron, which contained less phosphorus; and was likewise more extensible than that iron after exposure to a white heat. (*Conf.* No. 16, Table IV.)

The sample-bars numbered 21 to 25 in Table IV., which were filed out of an English rail and afterwards welded and rolled, contained nearly 0·25% of phosphorus, but very little

slag—judging at least from the appearance of the fracture. They had a specific gravity of about 7·6, were extremely cold-short, and broke with a crystalline fracture; but on breaking they were apparently not weaker than iron very poor in carbon and free from phosphorus. Probably they had been strongly heated immediately before the last rolling, and were afterwards not sufficiently stretched to develope a fibrous structure.

From the behaviour of iron rich in phosphorus, as recorded in the experiments above, it appears that phosphorus, like carbon, raises the limit of elasticity and strength *within* the crystalline particles of the iron (whence results the superior hardness of iron containing phosphorus); but that it does not increase the cohesion *between* the separate crystals.

Phosphorus, as is well known, renders iron more fusible, and increases its tendency to crystallize when heated. If, therefore, an iron rich in phosphorus has assumed a coarsely-crystalline texture by exposure to a strong heat, and has not afterwards been stretched sufficiently to bring the component crystals close together, and elongate them so as to develope fibre, such an iron may prove hard on wear, although neither extensile nor strong when stretched. For it is principally the cohesion *between* the crystals in the iron that is of importance, and not that between the particles *within* the individual crystals. The fracture of such an iron becomes, therefore, coarsely crystalline.

With reference to the Cleveland and Dudley irons, the unexpected tenacity of these bars, containing, as they did, so large an amount of phosphorus, doubtless resulted from the extension which they have suffered by rolling after the last reheating; and the development of a fibrous structure has probably been facilitated to a considerable extent by the intermixture of slag. In the sample of Cleveland iron (No. 12, Table IV.) the proportion of this slag amounted to 2·25%, and in another bar (No. 10, Table IV.) to 3%, whilst in the Dudley iron it was also 3%; but the latter, judging both from its appearance and from its behaviour on forging, generally

contained more slag than the former. The slag apparently has a tendency to oppose the aggregation of the crystalline particles of an iron rich in phosphorus, and hence it is that the irons previously mentioned have not been found cold-short even after exposure to a white heat. Other examples might be cited in which one substance when associated with another, although not in chemical combination, diminishes its tendency to crystallize. By extending the crystals so as to form fibre, the limit of elasticity is also lowered.

In an iron rich in phosphorus the intermixture of slag ought therefore to be beneficial, inasmuch as it considerably diminishes its tendency to become cold-short; but it is well known that the cinder makes the iron unsound, and renders it incapable of being worked without cracking. Of the different brands of English iron examined, only that from Low Moor was fit for smiths' work.

An iron that is cold-short, but free from slag, such as the Åryd iron, may, when heated, be readily stubbed, flattened, or re-formed in any other way, without cracking; but it is of course not suited for use where a high degree of tenacity is required.

23. *Influence of Phosphorus on Steel.*

With regard to the influence of phosphorus on steel, our knowledge is at present more imperfect than it is with reference to the effect of that element on iron. It is, however, generally assumed—and apparently with good reason—that the presence of phosphorus is more prejudicial in steel than in iron, and that the more phosphorus the steel contains the more readily does it lose its characteristic properties by repeated heating, so that at length it becomes impossible to temper such steel. The French chemist Caron, distinguished for his experiments on steel, explains this effect by supposing that the phosphorus, like silicon and sulphur, separates the carbon from its chemical combination with the iron. It is, however, known that those descriptions of steel which are most conspicuous for their power of enduring

several successive reheatings without perceptible alteration—such as the steel manufactured from Dannemora iron—are precisely those which contain the least amount of phosphorus; and the author knows no authenticated instance in which the proportion of phosphorus has been higher than 0·04% in what has been considered a good steel.

24. *Effects of Tempering, on the Limit of Elasticity, Extensibility and Absolute Strength of Steel and Iron.*

By exposure to a red heat and cooling in water, the limit of elasticity is raised not only in steel (as is well known), but also, though to a less extent, in soft iron. This is demonstrated by the following experiments:—A 12-feet bar of puddled iron from Motala was divided into two halves, of which one was examined in its unaltered state, and the other after being first tempered in water. In the former case (No. 30, Table IV.), the limit of elasticity was reached at 25,889 lbs., and in the latter at 27,996 lbs., or 2607 lbs. higher—all of these weights being of course reckoned on the square inch. Similarly, a bar of Cleveland iron was bisected, and the two halves heated together in order that they might be exposed as far as possible to like conditions of temperature. One half was then cooled slowly by being embedded in warm coal-dust, and the other part cooled quickly by immersion in water: in the former case the limit of elasticity was reached at 27,653 lbs., and in the latter at 29,437 lbs. Again, a bar of Surahammar puddled iron, branded G, after heating and slow cooling, had its limit of elasticity at 26,350 lbs., but by again heating the metal, and then cooling it in water, the limit was raised to 27,928 lbs. A bar of Lesjöforss soft iron, made in the English charcoal hearth, and containing only 0·08% of carbon, had its limit of elasticity raised under similar treatment from 18,527 to 31,839 lbs.; but on reheating and slow cooling, this limit was reduced to about 20,586 lbs.

A series of experiments was arranged in order to determine the effect which tempering exerts on the absolute strength

and extensibility of steel and iron; but as these experiments were not undertaken until the other investigations were nearly at a close, it unfortunately happened that bars suitable for examination were not at hand: nor was there sufficient time to carry out the experiments. The author therefore regrets that his researches on this point have not been so instructive as he could desire. The bars used for these experiments, many of which had previously been tested and broken, were generally from 0·8 to 1 foot each in length, and were filed square in the middle for a length of from 0·625 to 4·6 inches, so that they were always broken at the part filed.

The results of these experiments, which agree substantially with those obtained by the English experimenter Kirkaldy,[6] are given in Table VI., and show that the absolute strength in both iron and steel is increased by hardening, provided that the method employed is properly adapted to the quality of the material. That steel hardened in water and not tempered, becomes very brittle, doubtless results from the unequal contraction caused by the process of hardening, which induces so strong a tension between the particles that the exertion of a very slight external force is sufficient to overcome their cohesion.

25. *The Modulus of Elasticity: Different Statements of its Value.*

With regard to the value of the modulus of elasticity, or the measure of the elastic force, in iron and steel, and in different varieties of these materials, the results obtained by different authors exhibit considerable discrepancy. Thus according to Redtenbacher,[7] the modulus of elasticity expressed in English lbs. and referred to the English square inch as the unit, varies for iron between 21,272,200 and 35,545,160, and for steel between 28,477,300 and 34,104,140.

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6 'Experiments on Wrought-iron and Steel,' by David Kirkaldy. Glasgow, 1862, p. 93.

7 'Der Maschinenbau,' 1 Th., p. 4.

Reuleaux,[8] however, gives its value for iron, in the form of bars or wire, at about 28,477,300, for thin sheet-iron 34,154,240, and for cast-steel 42,681,640, but for other kinds of steel only 28,477,300. The results of experiments on tension by Lagerhjelm, Wertheim, and Hodgkinson do not, however, show such wide differences.

Recently the modulus of elasticity for certain kinds of iron and steel has been determined by Kupffer,[9] not, however, by means of traction, but partly by flexion and partly by transverse vibrations. According to his experiments, the modulus of elasticity has the following values expressed in lbs. per square inch for the different kinds of iron and steel mentioned below:—

	Sp. Gr.	Modulus of elasticity.
Iron plate, in the direction of the rolling	7·6763	25,066,886
Ditto, at right angles to the direction in which the rolling has been performed	7·6775	27,235,278
Rolled English band iron	7·6432	28,463,576
Forged English bar iron	7·6411	28,779,228
Forged Swedish bar iron	7·8315	30,357,488
Soft cast-steel	7·842	30,343,764
Steel from Remscheid (adapted for files)	7·8187	30,101,624

Kupffer also found that if the hardening by heat be avoided in hard steel, the modulus, when the steel is very hard, may be increased by nearly 6·5%. In most manuals of practical mechanics, such as Morin's, it is, on the contrary, stated that the modulus of elasticity in cast-steel is nearly 50% greater after hardening than before; and hence it would be supposed that hardening raises the modulus of elasticity.

Coulomb, Tredgold, and Lagerhjelm maintain, on the other hand, from their experiments, that the hardening has no influence on the value of the modulus of elasticity.

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8 'Der Constructeur,' p. 4.

9 'Recherches Expérimentales sur l'élasticité des Métaux, &c.,' par A. J. Kupffer. St. Pétersbourg, 1860.

To settle these conflicting statements would be of great practical importance in certain cases, as, for example, with reference to cast-steel in which the modulus of elasticity is, according to several authors, nearly 50% higher than in other kinds of steel and iron; so that cast-steel articles would spring only $\frac{2}{3}$ as much as similar articles of the same dimensions manufactured of the other materials. Induced by such considerations, the author determined, both by traction and by flexion, the value of the modulus of elasticity for those kinds of iron and steel of which he had suitable samples.

26. *Formula for Calculating the Modulus of Elasticity.*

The formula for determining the modulus of elasticity by traction is easily obtained as follows:—Let L and L′ denote the lengths of a bar when stretched by the forces P and P′, these forces being so chosen that they occasion no perceptible permanent elongation; let l represent its length when these forces have ceased to operate, a the sectional area of the bar, and E the modulus of elasticity of the material; then,

$$L - l = \frac{Pl}{aE}, \text{ and } L' - l = \frac{P'l}{aE},$$

$$\text{whence } L' - L = \frac{P' - P}{aE} l,$$

$$\text{and therefore } E = \frac{P' - P}{L' - L} \cdot \frac{l}{a}.$$

The last formula for the determination of the modulus of elasticity is that most used, since the bar when stretched is always somewhat bent, and therefore $L' - L$ can be measured more accurately than either $L - l$ or $L' - l$. To determine the length $L' - L$, as near as 1% or 2% is, however, by no means an easy task, at least for soft iron, whose limit of elasticity has been raised by stretching or other mechanical treatment. For in a 5-feet bar of such iron, $L' - L$ cannot be greater than about 0·023 inch, or at most three of our divisions of the scale. In this case a slight curvature in the bar of 0·012 inch may occasion an apparent difference in the elongation of more than

2%. Moreover, as previously stated, errors may arise in the reading to the extent of about 0·05 scale-division, and would thus introduce an error of more than 1·5%. Smaller errors may also arise from changes of temperature. In determining the modulus of elasticity, the author has therefore always enclosed the sample-bar in an apparatus which is represented in Pl. VII., figs. 1 to 4, and which will be subsequently described in detail. In this way, the bar under test has been surrounded by water, and therefore maintained at a nearly constant temperature, or at least any changes of temperature that might occur have been accurately determined. Moreover, it has been easy to ascertain by means of the index attached to the apparatus, that the bar has been so adjusted that the tensile strain may operate as nearly as possible centrally without flexure, and to measure any small variations in the curvature of the bar which may be produced by different strains.

27. *Description of Apparatus in which the Sample-bars are inserted for Determination of the Modulus of Elasticity.*

The apparatus referred to consists principally of a brass tube A, figs. 1 and 2, Pl. VII., through the middle of which the bar is inserted, and retained in position by two small brass fastenings *a, a,* which again are received by two short tubes *b, b.* These are clasped so tightly that no perceptible play is allowed; and in order that the bar may elongate and contract with the least possible friction, it is polished. Over the tubes *b, b* and the bar are placed some very narrow caoutchouc rings, and both these and the tubes *b, b* are bound by india-rubber tubing: this arrangement prevents the flow of water from the apparatus, whilst it does not impede the movement of the bar. When a sample-bar has been properly adjusted, a weight of from 2 to 5 lbs. has been sufficient to overcome the friction at both ends; and since it is sufficient that the bar during tension should move in one of the collars *a, a,* the resistance which is opposed to the elongation or contraction of the bar

cannot amount to more than one-half the force just mentioned; an amount too small to be taken into account. The two scales are firmly attached in the usual manner outside the caoutchouc tubes. The apparatus, intended to show variations in curvature, is represented in figs. 3 and 4, Pl. VII. It consists of two small steel bars *d, d,* the direction of which coincides with that of the axes of the tubes *e, e,* which are placed at right angles to each other, but inclined to the horizon at an angle of 45°. The upper pointed ends of *d, d* touch the indexes *f, f.* The bars *d, d* rest loosely on a well-filed brass plate, bent at a right angle and soldered on to the middle of the sample-bars, the sides of which plate have an inclination of 45° to the horizon, and are thus rectangular to the bars above-mentioned. The bars *d, d* may rest on the sample-bar itself, if this, having been originally round, has been filed square in the middle, for the purpose of investigating the position of the limit of elasticity at different temperatures. In the latter case, the bar must be so placed that the surfaces of the square portion are perpendicular to the bars *d, d,* as shown in fig. 4. Each of the needles *f, f* is moveable about a horizontal axis at *g,* and by means of a small spiral spring is forced to touch with its shorter and flattened arm the upper end of the steel bars *d, d.* These bars must therefore follow the transverse movements of the middle of the sample-bar in relation to the axis in the bearings *a, a*; and by means of the indicators F, F these movements may be accurately observed. The graduated arcs *h, h* are attached to the bars *i, i,* and may be raised or lowered by the set screws *k, k*; so that at the commencement of an experiment, or whenever it is considered necessary, each hand may be brought to the zero of the arc. The graduation of this arc is such that it indicates directly the amount of elevation or depression in the bars *d, d,* each division of the scale measuring about 0·5 line in length, and corresponding to a movement of 0·1 line in the bars. That the bars *d, d* may move freely up and down, they are secured not by packing, but by having thin caoutchouc tubing bound over both them and the ends of the tubes *e, e.*

28. *Correction of the Elastic Elongations as Measured.*

The amount of error which may arise from a small curvature in the bar can be estimated with sufficient accuracy in the following manner:—

It has been previously stated that, from the conditions under which these experiments were made, we may obtain the true length of the part between the fixed points of the scales, originally 5 feet long, in a slightly bent bar 0·46 inch thick, if we add to the measured length a quantity$=0{\cdot}0576\ h$ $\sin a + 0{\cdot}004\ h^2$. In this expression, h, as before, denotes the elevation or depression of the curvature of that part of the axis of the bar which lies between the two end markings, and a denotes the angle which the plane of the axis makes with the horizon.

By means of the apparatus last described we can now determine the manner in which the position of the axis in the middle of the bar varies in relation to two rectangular axes lying in a plane passing perpendicularly through the middle line of the bar; the axes being each inclined to the horizon at an angle of 45°, and cutting each other in the straight line which joins the middle line to the small brass fastenings, a, a, or, in other words, to the axis of the sample bars when perfectly straight. In fig. 4, Pl. II., which represents the plane of these axes, the axes are represented by X and Y. B is the centre of the axis of the bar; A is the projection of the points in the curved axis, which, when the bar is straight, lie vertically under the zero or fixed point of the scales; and O is the projection of the centre of the brass fastenings a, a. When the bar, as before stated, is curved in the arc of a circle corresponding to a very small angle, and the original distance between the zero points of the scales is 500 lines, and these points lie about 10 lines outside the middle of the short supplementary tubes b, b surrounding a, a; then A B or the height of the curve of the axis (h) is approximately $= \mathrm{BO}\left(\frac{500}{480}\right)^2 = 1{\cdot}085\ \mathrm{BO}$. If x_0 and y_0

denote the co-ordinates of the point B, referred to the axes X and Y, then because

$$\mathrm{BO} \cdot \sin a = \mathrm{BC} = \mathrm{DE} + \mathrm{BF} = \frac{x_0 + y_0}{\sqrt{2}},$$

$$\text{therefore we have } h \sin a = \frac{1 \cdot 085}{\sqrt{2}} (x_0 + y_0).$$

$$\text{Further, } h^2 = (1 \cdot 085)^2 \cdot \overline{\mathrm{BO}}^2 = 1 \cdot 177 \, (x_0^2 + y_0^2).$$

If now these values be substituted in the expression previously obtained for the difference between the actual and the measured lengths, and the former be denoted by L and the latter by l_0, we obtain

$$\mathrm{L} - l_0 = \frac{0 \cdot 0576 \times 1 \cdot 085}{\sqrt{2}} (x_0 + y_0) + 1 \cdot 177 \times 0 \cdot 004 \, (x_0^2 + y_0^2),$$

$$\text{and } \mathrm{L} = l_0 + 0 \cdot 0442 \, (x_0 + y_0) + 0 \cdot 0047 \, (x_0^2 + y_0^2).$$

In a new measurement under other conditions, when consequently the curvature of the bar is different, let L′ denote the actual length of the bar, and l_1 its measured length, and let x_1 and y_1 denote the new co-ordinates of the middle of the axis; then in a similar manner we obtain

$$\mathrm{L}' = l_1 + 0 \cdot 0442 \, (x_1 + y_1) + 0 \cdot 0047 \, (x_1^2 + y_1^2).$$

For the determination of the modulus of elasticity it is only necessary to know the difference between the actual lengths in the two cases, and this may be obtained thus:

$$\begin{aligned}\mathrm{L}' - \mathrm{L} = l_1 - l_0 &+ 0 \cdot 0442 \, (x_1 + y_1 - x_0 - y_0) \\ &+ 0 \cdot 0047 \, (x_1^2 + y_1^2 - x_0^2 - y_0^2).\end{aligned}$$

As the graduated arc must generally be so placed at the beginning that the hands *f*, *f* stand nearly at zero although the bar is not perfectly straight, it follows that the index cannot show the absolute value of the co-ordinates, but only their difference, or $x_1 - x_0$, $y_1 - y_0$, &c. If during the measurement the bar be extended by a moderate and suitable force, the co-ordinates should always be very small (in our experiments they rarely amounted to more than 0·3 line), and there-

fore the second term containing the difference between the squares of the co-ordinates may be neglected; whence[10]

$$L' - L = l_1 - l_0 + 0{\cdot}0442\ (x_1 + y_1 - x_0 - y_0).$$

When the temperature varies during the two measurements, this also must be corrected. If the temperatures at measurement of l_1 and l_0 be denoted by t_1 and t_0, and the coefficient of expansion by δ, we obtain, with regard both to variations in curvature and to changes in temperature, the corrected differences between the actual lengths of the bar in the two cases, thus:

$$L' - L = l_1 - l_0 + 0{\cdot}0442\ (x_1 + y_1 - x_0 - y_0) \\ - 500\ \delta\ (t_1 - t_0).$$

In employing this formula, which gives $L' - L$ expressed in lines, we must also express in lines the values of l_1, l_0, x_1, y_1, x_0, and y_0. But as in our measurements l_1 and l_0 were obtained in divisions of the scale, and it was also found convenient to take the indications of the hands f, f in tenths of a line, the formula last given was altered to facilitate calculation, as follows:—

$$L' - L = l_1 - l_0 + 0{\cdot}064\ (x_1 + y_1 - x_0 - y_0) \\ - 7248\ \delta\ (t_1 - t_0),$$

which gives $L' - L$ in divisions of the scale, when for $l_1 - l_0$ we substitute the differences between the measured lengths in those scale-divisions, and for x_1, y_1, x_0, y_0, the indications of the hands f, f, expressed in degrees of the arcs h, h, that is, in tenths of a line. It should also be noticed that in this formula x_1, y_1, x_0, y_0, must be taken positive when they are above zero, and negative when below. If, at the ordinary temperature, the coefficient of expansion δ for iron is

[10] In developing this formula it has been supposed that the bars are curved in an arc of a circle, but this supposition cannot generally be held for those bars given in Table VIII., and filed in the middle. The formula has, however, been applied to these, but the greatest attention has been paid to their insertion in the press, so that the changes in curvature become as small as possible.

0·0000118 and for steel 0·00001079, the formula becomes for iron:

$$L' - L = l_1 - l_0 + 0{\cdot}064\,(x_1 + y_1 - x_0 - y_0) \\ - 0{\cdot}085\,(t_1 - t_0),$$

and for steel:

$$L' - L = l_1 - l_0 + 0{\cdot}064\,(x_1 + y_1 - x_0 - y_0) \\ - 0{\cdot}078\,(t_1 - t_0).$$

29. *Measuring the Sectional Area.*

Next to the error which may arise from an incorrect determination of the value of the elastic elongation, it is necessary to guard against those errors which may be committed in measuring the sectional area; for in the determination of tensile strains and the length of the bars, the errors ought not to amount to more than a small fraction of 1%. The author has therefore used for these experiments the same bars which were employed in determining in what proportion the position of the limit of elasticity is dependent on temperature; each of these bars having been filed square with great accuracy for a length of about 4·5 feet in the middle. Some bars were also used which, having been carefully filed square, were subsequently employed in experiments on flexion. The modulus of elasticity has also been determined in certain round bars which have been filed only enough to remove the superficial scale formed by heating, and to level the principal irregularities of surface. It was found that the separate measurements of the area of such bars never differed from one another more than 1%; and the area of these bars did not always admit of being so accurately measured as that of the square bars. It will presently be shown that the modulus of elasticity in one and the same bar may vary several units per cent., according to the difference in the mechanical treatment to which the bar has been previously submitted. The area has always been measured at every half-foot by means of the micrometer-screw previously described, and the necessary corrections have been made for

differences in the threads at different positions of the screw. The same screws have also been used for controlling the dimensions in filing the sample bars.

30. *Probable Error in Values obtained for the Modulus of Elasticity.*

In spite of the author's endeavours to attain the highest degree of accuracy in these experiments, it is nevertheless *possible* that the values obtained for the modulus of elasticity may be incorrect, at least for soft iron, to the extent of a small percentage. But as the results given are the mean values calculated after at least 3, and sometimes even after 10 series of experiments, and as at least two microscopic observations and readings have been made at each measurement of length, it follows that the *probable* errors are very small; and in all cases the errors which have affected our observations are for practical purposes of no importance whatever.[1]

[1] As Wertheim used in his experiments, wire which according to his statement had a diameter of only from 0·1 to 0·5 line, he was but little exposed to error in respect of its curvature; but, on the other hand, he was unable to accurately measure its sectional area, except by calculating the mean area from the specific gravity. As the wires were only about 2·5 feet long between the points where the elastic elongations were measured, and as these measurements were obtained by means of a cathetometer, the values of the modulus of elasticity calculated by him from his experiments on traction, not unfrequently varied for the same iron and steel wire to the extent of 10 per cent. and upwards.

The modulus of elasticity may certainly be more accurately obtained by flexion than by traction, as the amount of deflection may be considerably greater, and therefore more accurately measured, than the elastic elongation by tension. But supposing that the value of the modulus of elasticity thus obtained is an exact measure of the elastic force on stretching, it is assumed that this force is equal to the elastic force on compression, whilst according to Hodgkinson the latter for iron is about $\frac{5}{8}$ of the former; and also that by different strains in different directions, and by the change of form in the sectional area which occurs on flexure, other forces are developed or the conditions are otherwise so changed that the calculations on the common formula become, as some authors affirm, uncertain. Wertheim in one case obtained the modulus of elasticity for steel wire more than 20% higher by means of transverse vibration than by traction. Kupffer's determinations of the modulus of elasticity by flexion and transverse vibrations agree very well *among themselves;* but, although the amount of deflection was determined in his experiments with great accuracy by affixing mirrors to the ends of the sample-bars and

31. *Example of Determining the Modulus of Elasticity.*

In order to show more exactly the precise method by which the experiments have been conducted, and also to show the degree of accordance obtained between different observations, the results are here given at length for the bars Nos. 2 and 10, Tab. IX.

On each bar eleven fine marks were drawn at distances of 0·5 foot apart, and then by means of the screw-measure the dimensions of each section at these marks were taken in two directions perpendicular to each other. These measurements gave the following results, expressed in turns of the screw:—

Bar No. 2.		Bar No. 10.	
Rectangular Section.		Circular Section.	
One Side.	Second Side.	One Diameter.	Second Diameter.
8·06	8·24	12·96	12·65
8·04	8·23	12·90	12·60
8·07	8·22	12·94	12·61
8·08	8·23	12·94	12·69
8·07	8·22	12·97	12·60
8·09	8·22	12·94	12·63
8·07	8·22	12·80	12·60
8·08	8·23	12·98	12·62
8·06	8·22	12·95	12·65
8·08	8·22	12·85	12·66
8·06	8·22	12·85	12·60
Mean = 8·069	8·2245	12·916	12·628

measuring the inclination which these mirrors assumed in different positions of the bars, yet his results *may* be affected by errors amounting at least to 1½ per cent., as his bars had a thickness of only 0·8 to 1·7 line. The third power of this thickness enters into the formula for calculating the modulus of elasticity by flexion, and therefore an error in measurement of 0·00058 inch, which for the thinner bars is more than ½ per cent. of their thickness, causes an error of upwards of 1½ per cent. in the modulus. That an error of measurement of this magnitude has been committed, may be seen by comparing the thickness measured with that calculated from the specific gravity.

To reduce these measurements to lines, it is necessary to obtain by a separate determination the value which must be used in each case, and as this value is 0·33652 for bar No. 2, and 0·33719 for No. 10, the sectional area of the former becomes = 7·515 square lines, and that of the latter, which may be supposed to be elliptic, = 14·565.

By two new measurements in other directions of the bar last referred to, the diameters at right angles to each other exhibited less difference; and as the area obtained from the one = 14·529, and that from the other = 14·434, it is assumed that the mean area of this bar = 14·509.

The bars were stretched several times successively: No. 2 first with a weight of 50 lbs. in the scale-pan of the bent lever, and afterwards with the lever alone, when this was counterbalanced by a weight of 50 lbs. suspended above; whilst No. 10 was stretched first with a weight of 60 lbs. in the scale on the lever, and afterwards with the lever alone. The results obtained are shown in Tables, pp. 64, 65.

As the bar No. 2 was about 2·7 lines thick, and as the planes of the scales were situated only 2·88 lines above the axis of the bar, the formula for correction of differences between the measured elongations consequently becomes:

$$L' - L = l_1 - l_0 + 0{\cdot}051\,(x_1 + y_1 - x_0 - y_0) \\ - 0{\cdot}078\,(t_1 - t_0).$$

In No. 10, however, the planes of the scales were situated, as was usually the case in these experiments, about 3·6 lines above the axis, and therefore for this bar the formula for correction is the one previously given, viz.:—

$$L' - L = l_1 - l_0 + 0{\cdot}064\,(x_1 + y_1 - x_0 - y_0) \\ - 0{\cdot}085\,(t_1 + t_0).$$

In the determination of the difference between the mean temperatures of a bar, $t_1 - t_0$, at two successive stretchings, we have always, for obvious reasons, given the indications of the middle thermometer twice the value of the two others.

No. of bar.	The temperature around the bar. At one end.	At the middle.	At the other end.	The indications of the hands *ff*. x	y	Total load on the long arm of the balance.	The position of the measuring-scale.[2]	Average.	The *measured* differences between the elongations $= l_1 - l_0$.	The *corrected* differences between the elongations $= L' - L$.
	Deg. Cent.	Deg. Cent.	Deg. Cent.	1-10th lines.	1-10th lines.	lbs.		Average.	Scale parts.	Scale parts.
No. 2 Tab. IX.	13·2	13·3	13·4	+ 0·1	+ 0·1	203·48	{104·317, 104·327}	104·322	7·002	6·8937
,,	13·2	13·4	13·4	+ 1·2	+ 1·2	47·51	{97·317, 97·323}	97·320		
,,	13·2	13·4	13·4	+ 0·1	+ 0·1	20·348	{104·353, 104·347}	104·350	7·018	6·9026
,,	13·2	13·4	13·5	+ 1·3	+ 1·2	47·51	{97·337, 97·327}	97·332		
,,	13·3	13·5	13·5	+ 0·1	+ 0·2	203·48	{104·363, 104·360}	104·3615	7·010	6·8978
,,	13·3	13·5	13·5	+ 1·2	+ 1·3	47·51	{97·350, 97·353}	97·3515		
,,	13·3	13·5	13·5	+ 0·1	+ 0·1	203·48	{104·350, 104·357}	104·3535	6·9885	6·8712
,,	13·3	13·5	13·5	+ 1·2	+ 1·3	47·51	{97·370, 97·360}	97·365		
,,	13·3	13·5	13·6	0	+ 0·1	203·48	{104·347, 104·367}	104·357	6·9955	6·8782
,,	13·3	13·5	13·6	+ 1·2	+ 1·2	47·51	{97·360, 97·363}	97·3615		
										Average = 6·8887

No. of Bar.	The temperature around the bar.			The indications of the hands *ff*.		Total load on the long arm of the balance.	The position of the measuring-scale.[2]		The *measured* differences between the elongations $= l_1 - l_0$.	The *corrected* differences between the elongations $= L' - L$.
	At one end.	At the middle.	At the other end.	x	y					
	Deg. Cent.	Deg. Cent.	Deg. Cent.	1-10th lines.	1-10th lines.	lbs.		Average.	Scale parts.	Scale parts.
No. 10 Tab. IX.	11·3	11·8	12	0	0	213·48	30·740 30·737	30·738	2·516	2·488
,,	11·5	11·9	12·1	− 0·4	+ 1·0	97·51	28·217 28·227	28·222		
,,	11·7	12	12·2	+ 0·2	+ 0·6	213·48	30·753 30·773	30·763	2·497	2·505
,,	11·8	12	12·2	− 0·4	+ 1·1	97·51	28·260 28·273	28·266		
,,	11·9	12·1	12·3	+ 0·2	+ 0·9	213·48	30·813 30·830	30·821	2·493	2·503
,,	12	12·1	12·4	− 0·3	+ 1·3	97·51	28·327 28·330	28·328		
,,	12·1	12·2	12·5	+ 0·6	+ 0·9	213·48	30·870 30·873	30·871	2·508	2·493
,,	12·2	12·2	12·6	− 0·3	+ 1·5	92·51	28·366 28·360	30·363		
									Average =	2·4972

[2] It is of course matter of indifference which division of the measuring scale is used at the beginning under the corresponding hair-cross of the microscope, provided that the fixed points of the scales are at the proper distance apart, viz., 5 feet exactly.

If now the formula for correction be applied, for example, to the differences measured between the elongations in the bar No. 2 at two stretchings, as given in the previous table, we obtain:

$$l_1 - l_0 = 7{\cdot}002\,;\ x_1 + y_1 - x_0 - y_0 = 0{\cdot}1 + 0{\cdot}1 - 1{\cdot}2 - 1{\cdot}2$$
$$= -\ 2{\cdot}2\,;\ \text{and } t_1 - t_0 = \frac{0{\cdot}1 \times 2}{4} = -\ 0{\cdot}05\,;$$

and if these values be inserted in the formula it becomes

$$L' - L = 7{\cdot}002 - 0{\cdot}051 \times 2{\cdot}2 + 0{\cdot}078 \times 0{\cdot}05 = 6{\cdot}8937.$$

When the value of $L' - L$ thus obtained is inserted in the formula for the modulus of elasticity, we obtain for the steel bar No. 2,

$$E = \frac{155{\cdot}97 \times 20{\cdot}084 \times 500}{6{\cdot}8887 \times 0{\cdot}06898 \times 7{\cdot}515} = 438{,}630,$$

or, in round numbers, = 439,000, or 30,124,180 lbs. per square inch. And in like manner for the iron bar No. 10,

$$E = 466{,}000, \text{ or } 31{,}976{,}920 \text{ lbs. per square inch.}$$

In calculating the modulus of elasticity for the bars Nos. 3, 8, 9, 14, 16, and 17, in Table IX., which bars have been filed in the middle, the formula becomes altered thus:

$$E = \frac{P' - P}{L' - L}\left(\frac{l}{a} + \frac{l'}{a'} + \frac{l''}{a''}\right),$$

where P, P', L, and L', have the same signification as before, but l denotes the length and a the mean area of the middle filed portion; and l' and l'' the lengths, and a' and a'' the mean areas of the short parts which were not filed.

32. *Causes which Affect the Modulus of Elasticity.*

In these investigations great attention must be paid to the diminution which the modulus of elasticity may suffer when the material has obtained a permanent set.

Although the modulus of elasticity generally decreases with the specific gravity, and the specific gravity is usually diminished by stretching the material, yet the decrease of the modulus referred to above, which in some of the experi-

ments amounted to 10%, cannot be satisfactorily explained by a diminution of specific gravity alone; for the modulus was usually greatest in steel, the density of which, as seen in Table VII., diminishes but very little on stretching. Moreover, the diminution of the modulus is, to a certain extent, only temporary. If the modulus of elasticity be determined in a bar *immediately* after it has obtained a permanent elongation amounting for instance to about 0·5%, and the bar be then set aside for several days, it will be found on renewing the experiment that the bar has regained a portion of the elasticity which it had lost by stretching; and the recovery of this elasticity is always greatly accelerated by heat. Among the numerous experiments in which we have had opportunity of observing this behaviour, it will be sufficient to cite those made with bar No. 3, Table IX., when this had been exposed to a moderate red heat, and its middle portion afterwards filed level. Its dimensions were then as follow (using the letters given in the formula for E), viz., $l = 468{\cdot}4$ lines, $l' = 17{\cdot}6$ lines, $l'' = 14{\cdot}0$ lines, $a = 7{\cdot}609$ square lines, $a' = 10{\cdot}746$ square lines. and $a'' = 12{\cdot}494$ square lines. When the bar at 60° F. was successively stretched by 170 lbs. on the scale of the lever, and then by the lever alone, the corrected differences between the elastic elongations, or L′ – L, became

	Scale Parts.	Mean.
	= 9·195	
	9·238	9·215
	9·213	
After a permanent elongation at the filed part of 0·72%, at the same temperature and with the same loads, L′ – L	= 10·267	
	10·240	10·256
	10·260	
And after the bar had been heated for about an hour in a bath of paraffine, at 266° Fahr., and was slowly cooled to 66° Fahr., L′ – L	= 9·427	
	9·415	9·411
	9·390	

As the elastic force in the round parts of the bars should have been the same in all the experiments, since those parts

did not receive any permanent elongation, and as many experiments have shown that an elevation of temperature to from 266° to 302° Fahr. does not sensibly affect the modulus in a material which has not been stretched, it was found that the differences between the elastic elongations in the square part of the bars was, on the average, as follows:—

Before stretching	8·8198 scale-parts,
After do.	9·8608 ,,
After heating	9·0158 ,,

If from these data we now calculate the value of the modulus of elasticity in this part of the bar under the conditions before mentioned, and assume that the permanent elongation of 3·44 lines obtained prior to the second series of experiments, diminishes the area to $\frac{468 \cdot 4}{471 \cdot 84} \times 7 \cdot 609$ (an assumption the more probable with regard to steel, since its specific gravity, as just stated, is very little affected by stretching), then the modulus becomes:

Before stretching	34,104,140 lbs. per sq. inch,
After do.	28,600,816 ,,
After heating	31,276,996 ,,

The elastic force of the material has thus been diminished by stretching 9·24%; but of this amount 8·53% has been regained by heating. When the bar was further heated for about an hour in a paraffine bath at 269° Fahr., and was again tested, the modulus was found to be the same as it was before this last elevation of temperature.

At the commencement of these researches we had no reason to presume that the elastic force would suffer any measurable change by an insignificant permanent elongation; and still less that when a bar had been stretched the modulus of elasticity would not remain unchanged when the bar was left at rest. The bars, therefore, previously to being stretched for determining the modulus of elasticity, received a slight permanent elongation in order to straighten slight curves, and to enable greater loads to be used in the determination of the modulus, and consequently to obtain greater elastic elongations which could be more easily measured. Since we have observed

the influence which slight stretching exerts on the value of the modulus, we have never stretched a bar with a greater load than that which was to be afterwards used for the determination of the modulus. It was not, however, always possible to avoid small, measurable elongations, and as it would appear that these are not without influence on the value of the modulus, they are noticed in Table IX.

The loss of elasticity caused by stretching may, as already stated, be restored to a great extent by moderate heating, and indeed if the heat be raised to redness, the modulus may become as great as it was before stretching, and even greater.[3] This is seen by the bars Nos. 2, 3, 4, 7, 13, 16, and 18, in Table IX., which bars have all been used for other experiments before heating, and have been stretched to a greater or less extent beyond their limit of elasticity. From this, it may be concluded that not only stretching, but also forging, rolling, or any other violent mechanical treatment, if not performed at too high a temperature, diminishes the modulus of elasticity in steel and iron.

From the table last referred to, it may also be observed that the modulus of elasticity generally increases with the specific gravity—a relation already pointed out by Lagerhjelm; that it is not very different for different kinds of steel, or for steel and iron with the same specific gravity; and that it is not specially influenced by the amount of carbon; but that the value of the modulus is in no small degree dependent on the proportion of phosphorus present. The lowest modulus of elasticity has been found in the iron from Åryd, which is rich in phosphorus, although its specific gravity is about equally high with that of the better kinds of puddled iron which were examined.

With regard to the influence of hardening on the modulus of elasticity on tension, we have not been able to undertake

[3] Both Coulomb and Tredgold deny that a red heat has any influence on the value of the modulus, and base this denial upon some of their own experiments on flexion; but their measurements of the deflection appear to have been not sufficiently delicate to detect so slight a difference as is here alluded to.

any investigations, for among the kinds of steel at our disposal we have not succeeded in hardening any bar of the requisite length without its becoming too much bent to be employed in these experiments. We have therefore been obliged to confine ourselves to the examination of the effect of hardening on the elastic force at flexion,—a point of even greater importance in a practical aspect; and to this subject we shall therefore return in describing the experiments on flexion.

33. *Résumé of the Results.*

After this account of our experiments on tension performed at the ordinary temperature, it seems desirable to give a brief summary of the results at which we have arrived. These results, which in part simply confirm those of other observers, are as follow:—

1. The limit of elasticity, in the sense in which that expression is generally understood, or as it is defined by Wertheim and other observers, cannot serve as a guide to the determination of the different elastic qualities of metals, inasmuch as it does not admit of being determined with the requisite degree of accuracy. On the contrary, an easily-determined measure of the limit at which any permanent elongation of practical value first occurs in iron and steel, may be obtained if the limit of elasticity be defined, as in our new definition at p. 30.
2. The amount of permanent elongation produced by stretching iron and steel is dependent not only on the chemical constitution of the material, the manipulation to which it has been subjected, and the regularity of its section, but also on the method by which the traction is effected. These elongations generally increase more rapidly than the excess of the loads above those at the limit of elasticity; but it may be assumed that they are approximately proportional to this excess.

3. The limit of elasticity, the absolute strength, and the extensibility, are to a great extent dependent, in both iron and steel, on the mechanical treatment to which the material has been submitted, and on the temperature to which it has been exposed, either during working or subsequently. By cold-hammering, cold-rolling, and other forms of mechanical treatment applied at a low temperature, both the limit of elasticity and the absolute strength are increased; whilst by the same treatment the extensibility is diminished. In these respects heating produces an opposite effect.
4. When the proportion of carbon in iron or steel is increased whilst other conditions remain the same, the limit of elasticity, as well as the absolute strength, is to a certain extent increased; but the extensibility, on the contrary, is diminished. The absolute strength, which in good soft iron may be estimated in round numbers at 48,034 lbs. or 21·44 tons per square inch, seems to attain its maximum in steel containing about 1·2 per cent. of carbon, and is then in good cast-steel or Bessemer steel about 137,240 lbs. or 61·26 tons per square inch.
5. A small proportion of phosphorus in iron generally raises the limit of elasticity and the absolute strength, and therefore also the hardness of the metal, but at the same time it diminishes its extensibility; provided that the iron during its manufacture has been so much drawn out that on slow rupture it exhibits a fibrous fracture.

   By admixture, however, of slag (which always makes the iron unsound and difficult to be re-formed when heated, but which facilitates the development of a fibrous structure) an iron containing about 0·25% of phosphorus seems capable of acquiring nearly the same extensibility as an iron which contains only traces of phosphorus. The presence of slag also seems to

oppose the tendency of the iron to become, when strongly heated, crystalline, and therefore cold-short.

6. By heating and sudden cooling (hardening), the limit of elasticity is raised whilst the extensibility is diminished, not only in steel but also in iron. The absolute strength likewise is increased by hardening, if this be performed in a manner adapted to the quality of the material. Hardening in water without subsequent moderate heating (tempering) generally diminishes the strength of hard steel to a very considerable extent, whilst hardening in oil does not occasion this inconvenience, provided that the heat previous to hardening has not been too high.

7. The elastic force which iron and steel develop on stretching is not always equally powerful in the same material, but is dependent on the manner in which the metal has been previously treated. Thus, by such mechanical operations as stretching, hammering, &c., the elasticity may be diminished; whilst by a moderate heat, or still better by a glowing heat, it may be increased. Moreover, it does not vary to any great extent for different kinds of steel, or for steel and good iron; but it generally decreases with the specific gravity. The measure of this force, or the modulus of elasticity, may be estimated in round numbers at 30,879,000 lbs. per square inch for rolled or forged bars having a specific gravity of about 7·80, and containing only a trace of phosphorus; but for iron bars in which the material is very cold-short or contains a considerable proportion of slag, it is only about 27,458,000 lbs. per square inch. On the contrary, in Bessemer iron with a specific gravity of 7·88, the modulus of elasticity may rise to about 34,310,000 lbs. per square inch.

CHAPTER II.

APPLICATION OF THE RESULTS TO THE DETERMINATION OF THE RELATIVE VALUES OF IRON AND STEEL, AND DIFFERENT KINDS THEREOF, FOR DIFFERENT PURPOSES.

1. Preference of steel to iron for such purposes as require a combination of strength and lightness. — 2. And for such as require strength and hardness to resist wear. — 3. Importance of extensibility in materials employed for machinery and buildings. — 4. Relative capacity of steel and iron to endure sudden shocks. — 5. Best material for articles occasionally subject to severe shocks. — 6. Choice of material for articles commonly subject to slight shocks or vibrations. — 7. Most suitable degree of hardness for steel to be used for tyres, axles, &c. — 8. Employment of iron which has become stiff by mechanical treatment. — 9. And of iron containing phosphorus. — 10. And of iron containing slag. — 11. Advantages of a pure iron for general forgings.

1. *Preference of Steel to Iron for such purposes as require a combination of Strength and Lightness.*

IN consequence of the considerably greater strength of steel, and of the much higher position of its limit of elasticity, the dimensions of articles manufactured of this material, may be smaller than when iron is employed; and, therefore, the use of steel offers considerable advantage over iron for such objects as require to be made as light as possible, such as the motion-parts of machinery, vessels, all rolling-stock, &c. The application of steel to these purposes is daily becoming more general; and in England, especially in the great ship-yards of Liverpool, there are now being built on a large scale both steam and sailing vessels constructed either entirely or for the most part of steel. It is said that such a vessel is so much lighter than one of iron of the same size and strength, that it can carry 25% greater cargo; and that it has the further advantage of drawing less water, and, therefore, of being able to enter ports and passes

which would be inaccessible to an iron vessel with the same cargo. For bridges with a large span, lightness is of the highest importance, as a much greater part of the strength of the material is required to support the weight of the bridge itself than to bear the additional weight of the greatest load that may pass over it. In Holland a bridge has lately been constructed of so expensive a material as cast-steel; and in Sweden a bridge of puddled steel from Surahammar was built in 1865 over the river Gotha on the railway between Wenersborg and Herrljunga. As, however, the modulus of elasticity is nearly the same for steel as for good iron, it follows that a steel bridge, in consequence of the smaller dimensions of its several parts, must spring more than an iron bridge of the same construction and same strength; and if this vibration is to be avoided, the construction must necessarily be altered.

2. *Preference of Steel to Iron for such purposes as require Strength and Hardness to resist Wear.*

Steel—and especially cast-steel, which unites with hardness and strength a high degree of homogeneity—should be preferred to iron for all purposes which require not only strength but power of resistance to wear, such as rails, axles and tyres for railway-carriages, piston-rods, and other parts of machinery. The value of steel for such purposes has long been recognized, and the only great obstacle to its extensive employment hitherto has been the high price of cast-steel. This obstacle has, however, been to a great extent removed by the discovery of the Bessemer process, and by the improvements which within the last few years have been introduced into the manufacture. Already Bessemer steel has been largely employed for rails laid down at railway stations and points, or on sharp curves and strong gradients, and in general for rails in any situation where they are exposed to more than ordinary wear. According to experiments made in England at the Chalk Farm Station, Camden Town,

where the traffic is so great that common English iron rails had sometimes to be renewed after a few weeks' wear, it appeared that rails of Bessemer steel could stand nearly twenty times the wear of ordinary rails, although the manufacturer did not guarantee them to be more than six times as durable. If the amount of wear for ordinary rails can be estimated from the traffic and the speed, it is easy to determine exactly when Bessemer rails can be employed consistently with economy, although their original cost is more than double that of the others.[4] Rails having only the upper

[4] This was no doubt the case at the time the author wrote; but the price of Bessemer steel rails has since been continually lowered until it is now (Nov. 1868) hardly more than 50% above that of iron rails. Indeed, the cost of making rails by the Bessemer process is no greater than by puddling, but the former requires a purer raw material or pig-iron to start with; and as this will probably not involve an increase in price of more than 25% on the rails, it may be easily seen that great economy would result from the more general use of steel rails. This question was brought before the Institution of Civil Engineers and carefully discussed in March, 1868.

At the same time the question of steel-headed rails was also discussed, but the general opinion amongst Railway engineers was decidedly against them. The translator having superintended at the Dowlais Works the execution of an order for this kind of rails for the Swedish Government railways, suggested some alteration in the mode of manufacture. Arrangements were made with the South Eastern Railway Company to have some of the rails that had been made on this principle, tried on their line. The result is shown in the following letter, dated March, 1868; to which it may be added, that even now (Nov.), the rails remain in excellent condition, not one of them having given way through the top coming off. These rails. indeed, show hardly any abrasion after 9 months' wear with about 150 trains passing over them every 24 hours.—*Translator.*

(*Copy.*) South Eastern Railway, Engineer's Office,
5, St. Thomas's Street, London, S.E. March 31, 1868.

Steel-topped rails.

DEAR SIR,—The 6 rails you were so good as to send me have been laid on the road at London Bridge, in the most trying situation.

I am pleased to be able to inform you that they are standing, and look remarkably well.

This Company had previously tried some so-called steel-topped rails from another firm, which were a complete failure in a month's trial.

I was not at all astonished to hear the general condemnation of steel-topped rails at the Institution; but it is right to say that, after the test yours have already gone through, there are yet hopes of permanent success in that description of rail.

Yours truly,
(Signed) PETER ASHCROFT.

C. P. Sandberg, Esq.

part (the head) of Bessemer steel, the rest being of iron, are at present manufactured on a large scale. Such rails are of course much cheaper, but are difficult of manufacture, and would not probably bear equal wear with rails consisting entirely of Bessemer steel.

Railway axles and tyres of Bessemer steel are also largely manufactured even in Sweden. With regard, however, to its suitability for such purposes, opinion is not quite so favourable as it is with reference to its undoubted superiority for rails. This has probably arisen from manufacturers having at first exported goods in which the material was perhaps not quite free from flaws, or was too hard, so that it did not possess sufficient extensibility.[5]

3. *Importance of Extensibility in Materials employed for Construction of Machinery and Buildings.*

A certain degree of extensibility is indispensable, not only in the material of those articles previously referred to, but in

[5] This was no doubt generally the cause of the failure and of the irregularity in the strength of the Bessemer steel when the process was first introduced; but by degrees a more careful assortment of the steel has been established at nearly all Bessemer Steel Works, the hardness of the material being determined partly by the test of forging, and partly by Eggertz's colouration test. This has greatly added to the security of the manufacture; but it has lately been observed, as well in England as in Styria, that silicon may play the part of carbon in steel by rendering it hard. This again has caused some difficulty in the assortment of the steel, as in such a case the two modes of examination are discrepant; the chemical test showing a very small amount of carbon, whilst the forging test shows a hard steel. This occurs, however, only when the pig-iron employed contains a large proportion of silicon and but little carbon, as the latter element is burnt away before all the silicon is removed; which shows, however, that both of these constituents are simultaneously carried off, and not as formerly believed the silicon first and the carbon afterwards. Such inconvenience may however be obviated by properly regulating the proportion between the silicon and carbon in the pig-iron.

Another cause of the failures of Bessemer steel is to be found in the raw material for particular purposes, such as axles and tyres, not having been more carefully selected or of better quality than that used for rails. Plate IX. shows that Bessemer steel, made from good charcoal pig-iron and of the same hardness as cast and puddled steel possesses equal strength and extensibility. —*Translator.*

most other parts of machinery or of buildings which may be supposed to allow, without fracture, any slight alteration of form that may arise from irregularity in the construction or from any extraordinary strain. The importance of this should by no means be overlooked in those structures which consist of several separately-wrought pieces, such as an iron bridge or a boiler; for these can never be so constructed that the strain is from the beginning evenly distributed throughout. If then the component parts are not sufficiently extensible, they may be broken successively long before reaching the strain for which the bridge or the boiler was calculated. In such a case the elastic elongation which the separate parts could assume is commonly an insufficient guide.

When the parts, in order to be joined together, have become weakened at any point, either by some of the material having been removed as by riveting, or by the material having at any point been overheated, it must by no means be expected to show *in all parts* as great an extensibility as it exhibited in experiments on tensile strength. If, however, we know to what extent a bar or a plate has been weakened at a certain part by diminution of area, or by heating, and also know the limit of elasticity in the other parts of the material, together with the absolute strength and elongation on rupture, it will then be easy to estimate approximately, in every case, the elongation which the bar or plate may assume before being broken. If, for instance, a stay be taken, manufactured of soft steel with a limit of elasticity at 41,172 lbs., and the breaking load at 68,620 lbs. per square inch, and which, on fracture, has shown an elongation of 10%; and if the area, at any part, has been diminished 20%, or the absolute strength of the material has been lowered to the same extent by overheating, then that the stay must break with 0·8 of the strain required to break the unweakened part of the bar (that is, when the load at this part amounts to nearly 54,896 lbs. per square inch); but, since the permanent elongation, as previously shown, will increase almost in the same proportion

as the excess of the loads above those at the limit of elasticity, and this increase is generally greatest when approaching fracture, the stay, therefore, when loaded with 54,896 lbs. per square inch can elongate, at most, only half as much as with the load of 68,620 lbs. on the same area, or 5% of the original length.

If the absolute strength were diminished at any place, to the amount of 60% of the original strength, the stay would (under the same conditions and if made of the same material) break with a strain of 41,172 lbs. per square inch on the unweakened part: thus rupture would take place at the limit of elasticity and, consequently, before the part last mentioned could assume any considerable elongation.

In like manner, if in riveting an iron plate, whose absolute strength is 48,034 lbs. and the limit of elasticity 30,879 lbs. per square inch, the riveted part becomes 40% weaker than the rest, it is of little avail that the plate possesses great extensibility, for it will break at the rivets when the strain on the other parts reaches 28,820 lbs. per square inch, and it can then only give way a little in the actual line of rivets. If, however, the plate were constructed of puddled steel, Bessemer steel, or cast-steel, having a breaking strain of 68,620 and a limit of elasticity of 34,310 lbs. per square inch, and could elongate on fracture 10%, but was only 0·7 as thick as the former plate; then, on the same supposition with regard to the strength of the riveted portion in relation to the rest, the part riveted would break with the same absolute weight as in the previous case, corresponding to 41,172 lbs. per square inch on the rest of the steel plate; but the plate last mentioned has elongated nearly 2%, that is, almost ¼ inch per foot. The latter structure would, therefore, be more worthy of reliance than the former, although it required 30% less material.

As the ratio of the breaking load to the limit of elasticity is generally greater in rolled puddled steel and other kinds of soft steel than in puddled iron, the employment of such steel would consequently allow the structure to assume a

greater change of form than would be permitted if soft iron were employed. When, however, these materials are compared with each other in the form of *homogeneous* bars, the steel usually shows less extensibility.

From what has now been advanced with reference to the disadvantage of weakened points in machinery and building structures, it will readily be understood how desirable it is, both for economy and security, that the girders and stays employed in the construction of lattice-work and suspension-bridges should have bosses or swellings at the points where they are penetrated by bolts or rivets.[6]

In employing steel for purposes in which the material must be heated for further working, especial attention should be paid to the diminution of strength consequent upon such heating. For this diminution, as proved by the experiments on fracture, is greater in steel than in iron; and in different kinds of steel is greater according as the metal is harder, or richer in carbon.

4. *Relative Capacity of Steel and Iron to Endure Sudden Shocks.*

Some authors have asserted that steel, in consequence of its great strength, is indeed well adapted for any purpose in which it is exposed to strains that operate only gradually, but that it is on the contrary quite unfit for any purpose in which the material is exposed to sudden shocks or blows. In order to determine how far this assertion is true, we will examine the effect of a sudden shock applied to a bar in the direction of its length when the bar is steadily fixed at one end; and also when acting from above in a vertical direction on the middle of the bar, the free ends of which rest on two solid supports.

If P_1 denote the force which when gradually stretching a bar is sufficient to produce fracture, a_1 the elastic elongation of the bar, and b_1 its permanent elongation at fracture, then

[6] How such bars are worked is described in the *Jernkontorets Annaler*, 1862, p. 316.

the mechanical force necessary to break the bar slowly, or to produce the elongation $a_1 + b_1$ is expressed (as will easily be seen[7]) by $\frac{P_1 a_1}{2} + m P_1 b_1$, where m is a quantity which lies between 0·75 and 1.

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[7] If we represent by p the force with which the bar is strained when the extension is performed gradually; by a and b the same force corresponding to the elastic and permanent elongations, which of course both vary with p; by P_0 the force corresponding to the limit of elasticity; by b_0 the permanent elongation of the bar at this limit; by A the sectional area of the bar; by L its length, and E its modulus of elasticity; if P_1, a_1, b_1 and m have the same signification as given above, then the mechanical force required to break the bar, and which we will denote by M, $= \int_0^{a_1} pda + \int_0^{b_1} pdb$. The modulus of elasticity, E, certainly diminishes somewhat, as previously shown, when the bar begins to obtain a permanent elongation; but in an approximative calculation, such as that here given, we may regard it as constant and give it a mean value. Then because $p = \frac{a\,E\,A}{L}$, and $a_1 = \frac{P_1 L}{E\,A}$, therefore

$$\int_0^{a_1} pda = \frac{E\,A}{L}\int_0^{a_1} ada = \frac{E\,A}{L}\cdot\frac{a_1^2}{2} = \frac{P_1 a_1}{2}.$$

Further, $\int_0^{b_1} pdb = \int_0^{b_0} pdb + \int_{b_0}^{b_1} pdb = \int_0^{b_0} pdb + (b_1 - b_0)\,P,$

where P denotes a value of p which lies between P_0 and P_1, but which is always greater than $\frac{P_0 + P_1}{2}$, because the permanent elongations increase in greater proportion than the excess of the loads above that at the limit of elasticity. Since, too, P_0 is in most cases greater than $\frac{P_1}{2}$, P is also greater than 0·75 P_1; and as b_0 very rarely amounts to more than 0·1 %, and is usually much less, it may be presumed that $\int_0^{b} pdb = m\,P_1\,b_1$, and thus $M = \frac{P_1 a_1}{2} + m\,P_1\,b_1$. The relative value of the mechanical forces required to fracture bars of different sorts of iron and steel of the same dimensions, may most easily be determined by graphically representing the permanent elongations produced by gradual stretching, in the manner shown in Plates III. and IV. $\int_0^{b_1} pdb$, or the quantity $m\,P_1\,b_1$, corresponds, for each of the bars, to the surface limited by the curve of elongation and the co-ordinates of the final point of the curve; and the quantity $\frac{P_1 a_1}{2}$ might be represented by a right-angled triangle, of which one side would be the ordinate of the final point of the curve corresponding to P_1; and the other side a portion of the abscissa-axis measured to the right of the point where the ordinate referred to intersects the abscissa-axis, and which $= \frac{100\ P_1}{E}$, as the entire value of M was represented by a single connected surface.

The mechanical force necessary to break a bar which rests free on two perfectly solid supports, can also be represented, as shown by experiments on flexion, by this same formula, if P_1 denotes the force which when applied to the middle of the bar and gradually operating produces fracture, and a and b denote respectively the elastic and permanent deflection of the bar, corresponding to the force P_1. A bar of good iron resting free on two supports cannot, however, generally be broken by the load, and therefore our formula only expresses the mechanical force which gives the bar a greater or less permanent deflection b_1.

The mechanical force necessary to break or strain different bars when acting *gradually* is not strictly the same as that required to break or strain the same bars when acting *suddenly*. For in the latter case the force P may possibly be somewhat different,[8] and the permanent elongations and deflections which precede fracture or strain are generally somewhat less.[9] On the other hand, there is no reason to

[8] Kirkaldy concludes from his experiments that the force required to suddenly break a bar is, on an average, not more than 80% of the breaking load at gradual fracture. But this conclusion cannot be correct, as he paid no regard to the fact that, in his apparatus for stretching, the load at sudden fracture must acquire a certain *vis viva* before it can be entirely supported by the sample bar, and that this bar must therefore also resist the effect of this *vis viva*. Wertheim, on the contrary, asserted that a greater force was required to fracture a bar rapidly than slowly.

[9] The amount of permanent deflection occasioned previous to fracture by a load or a shock acting gradually, is greatly dependent on the manner in which the load or shock operates. Each bar may be bent in a certain circular arc, and the radius of this arc is smaller the greater the ductility of the material. If the force acts at the middle by means of an edge or a very small surface, the curve becomes sharper there, and the amount of curvature which the bar may assume before fracture is less than if the force operated upon a larger surface, and the curvature was therefore distributed over a greater length. This circumstance must not be lost sight of when rails, axles, and similar objects, are tested by a gradually-applied load, or by means of a falling ball.

[The translator, when inspecting railway materials, such as axles and rails of iron or steel, has always applied a short piece of an iron bar 1½ in. square on the top of the rail or the axle; the object of this piece being to receive the falling ball, so that the effect of the blow may be confined within reasonable limits; for, as the balls used for this purpose are generally made too flat at the bottom, they must lessen the effect of the blow.—*Translator.*]

presume that the value of the mechanical force, calculated in the manner above indicated, should not express with sufficient accuracy for practical purposes the *relative* value of the forces required to break different kinds of iron and steel when acting suddenly.

Every shock corresponds to a certain mechanical force, and if a shock be applied either in the direction of the length of a bar when firmly fastened at one end, or to the middle of a bar resting free on two solid supports, that bar must break if the force corresponding to the shock is greater than[10] $\frac{P_1 a_1}{2} + m P_1 b_1$. Knowing the qualities of iron and steel, it is easy to determine that this expression is much greater for soft iron than for hard steel. For in hard steel when hardened, $b_1 = 0$ very nearly, or is very small relatively to a_1, and therefore the mechanical force necessary to rupture or strain such a bar depends mainly on the value of $\frac{P_1 a_1}{2}$. On the contrary, for unhardened steel and for iron, b_1 is in general considerably greater than a_1, and therefore the mechanical force necessary to rupture or strain such bars depends chiefly on the value of $m P_1 b_1$, which, as shown in Plates III. and IV., is greatest for soft steel and iron, in consequence of their greater ductility or tenacity.

As the tougher material may yield to a greater extent when affected by a shock, it may thus longer resist the effect and may sustain a more violent shock than if it were twice as strong, but had only one-fourth the extensibility, although the amount of its power of resistance would be greater in the latter case. It may now be readily understood why a bar

[10] As the supports of the bar can never be *perfectly* solid so that they do not shake, they always receive a portion of the shock, and thus vibrate. When the supports are, *e.g.*, large masses of iron, this may be too insignificant for notice; but when they vibrate much, or assume any permanent set, the portion of the shock which they receive may actually be greater than that received by the bar. This should be particularly remembered in testing iron and steel objects by the blow or shock of a falling body. (See Remarks on this by the translator in the Appendix.)

of iron can, by assuming a great permanent change of form, sustain a shock which would break a hard steel bar of the same dimensions, although the latter is able to carry a greater load if acting gradually.[1]

5. *Best Material for Articles which* occasionally *are subject to* Severe Shocks.

For articles which *may* be exposed to *severe shocks,* the quality of the material should always be selected with regard to the greater or less probability that a violent shock may occasionally have to be sustained, and to the probable effects of such a concussion. In those articles which, when subjected to very severe shocks may, without any great danger, assume a considerable change of form, but whose fracture would entail important consequences (such as armour plate), the material must necessarily possess great toughness.[2] In other cases, as in certain parts of machinery, the inconvenience attending a change of form may be as great as that consequent upon rupture, if not indeed greater; and therefore in the choice of the material for such purposes strength must be considered as of first importance, and extensibility as secondary.

[1] The formulæ for resistance to shocks given by Redtenbacher and Weissbach are to a great extent erroneous, especially with reference to a very extensible material such as soft iron, since these authors in the derivation of their formulæ disregarded the permanent change of form, and supposed that the alteration of form in the material followed the same law when the limit of elasticity was exceeded as before it was attained. According to the coefficients given by Redtenbacher in his *Der Maschinenbau* (vol. i. p. 95), the very absurd result is obtained that a bar of cast steel should require, in order to be broken, from 6 to 12 times as strong a shock as an iron bar, and this latter could endure but very little more than a bar of cast iron, supposing that the dimensions of all the bars are alike, and that the shock is applied in the same manner.

[2] In determining the power of resistance to shocks applied as suddenly as those of projectiles, there is but little deviation from the formula previously given; because that part which is immediately struck by the moving body may be easily broken from the rest before there has been time for the shock to impart its effects to the surrounding material. In such cases it is always desirable that the material possesses in addition to ductility great strength to resist fracture. Soft cast steel is therefore no doubt better suited *e.g.* for cuirasses, than is very soft iron. The problem, however, involves many points difficult of solution.

6. *Choice of Material for Articles* commonly *subject to* Slight Shocks *or Vibrations.*

For articles which are exposed during wear to a rapid succession of small shocks or vibrations, and which must therefore have such dimensions that each of these shocks cannot produce any perceptible alteration of form, it would generally be most suitable to select medium hard steel containing from 0·5 to 0·7 per cent. of carbon; for its limit of elasticity is higher than that of iron, and it possesses so great an extensibility that when rolled and free from flaws it may be elongated by traction from 5 to 15%, or even more; added to which, it is at least 50% stronger than soft iron. The limit of elasticity, like the strength, may certainly be raised to a very great extent by hardening, but to do this requires considerable experience and a special knowledge of the material: moreover, the effects of hardening are in general very difficult to determine, at least for articles of large dimensions. By hardening, there is often induced in the material so strong a tension that the application of only a very slight external force is sufficient to produce rupture. According, however, to our experiments, hardening in oil is attended with less risk, provided that the articles have not been too strongly heated.

The selection of a material at once strong and stiff, and yet in a certain degree extensible, is of especial importance when the shocks affecting the material do not always operate in the same direction, as in the axles of locomotive engines and steam-boats, &c. For such injury does not, as in many other cases, produce a set which soon becomes constant; but if the material is not sufficiently stiff, or if the structure is too weak, it causes continual change of form, sometimes in one direction and sometimes in another, and consequently the material sooner or later *must* be broken. That in such a case steel is preferable to iron, in consequence of its superior strength, has been proved by the experiments which, at the request of the Committee, were undertaken at Taberg in Wermland, under the direction of Professor C. A. Ångström.

Bars of iron and steel were tested in an apparatus of a construction essentially similar to that employed for a like purpose by the German mechanician Wöhler, and described in Erbkam's *Zeitschrift für Bauwesen* for 1860. In this machine the bars under rotation are subjected, until broken, to a strain similar to that suffered by railway axles. For the details and results of these experiments, reference must be made to the account which will shortly be published by Professor Ångström.

7. *Most suitable Degree of Hardness for Steel to be used for Tyres, Axles, &c.*

In determining the degree of hardness of steel best adapted to special purposes, regard must be had to the circumstances under which the articles will be employed, and to their method of manufacture. Thus, for example, with regard to those important objects railway tyres, the degree of hardness selected should have reference to the method of fixing the tyres on to the wheels, and to the greater or less security from fracture which it is necessary to attain, as also to the method of manufacturing the tyres themselves.[3] If the tyres are made solid without welding, so that after having once left the rolling-mill they need not be again exposed to heat, beyond what is necessary for fastening them to the wheels, the proportion of carbon may without any risk amount to 0·6%; but if they are made of bars bent and welded together, and fastened on to the wheels by bolts in the usual manner, we could not venture to recommend the employment of a steel containing more than about 0·4% of carbon, for the part at

[3] The economy of using steel instead of iron for railway tyres depends greatly upon its hardness, for it is evident that the harder the steel the longer it will wear. Safety, however, is a still more important point. Both these conditions may be attained by adopting retaining-fastening, that is to say, such a mode of fixing the tyre to the wheel that it cannot fly off even when broken. These retaining rings, used on Mansell's wooden wheels as well as on common iron wheels for railway carriages, have given highly satisfactory results.—*Translator.*

the welding becomes comparatively weaker the harder the steel employed. Even for solid rolled tyres manufactured on Krupp's plan,[4] a harder steel may be used than for tyres rolled from cast rings.

Krupp is said to employ for axles of steamboats, locomotives, and machinery, cast steel containing from 0·5 to 0·6% of carbon; and for axles of passenger-carriages steel with a little more than 0·6% of carbon.

When the proportion of carbon in Bessemer steel and cast steel is as low as 0·4%, or even less, and the steel is not drawn out at too low a temperature, the elongation on fracture may amount to 16% or upwards (*Conf.* Nos. 20 to 24, Tab. IV.), and the extensibility consequently becomes as high as in good puddled iron. As such steel is not only much stronger than soft iron, but is in general also sounder and more homogeneous than a product obtained by puddling or by refining in the hearth, there can be no doubt that it should be preferred to such iron for most purposes in which great extensibility is desirable or necessary—such as ship-plates, boiler-plates, objects struck cold by the die, and such articles as may require to be tinned or coated with another metal.

8. *Employment of Iron which has become Stiff by Mechanical Treatment.*

As we have seen how soft iron containing a small amount of carbon may, by suitable mechanical treatment, be made to exhibit a high degree of stiffness and strength, it is evident that for certain purposes such iron may, to some extent, replace steel. In such a case, however, several conditions are necessary in the material. In the first place, its dimensions must be so small that it *can* by mechanical treatment be made sufficiently stiff; after having been submitted to this treatment, it must not be reheated for further working, or exposed

[4] *See* 'Jernkontorets Annaler, 1862, p. 335.'

to heat during use, because in that case the elasticity and strength derived from the mechanical treatment would be lost; and, further, the material must not be required of any great degree of hardness or power of resistance to wear. Iron wire that has been hard drawn is therefore generally used for springs in furniture, and cold-hammered iron for the smaller springs of carriages, &c., but such iron cannot be advantageously employed for larger springs, axles, &c.

9. *Employment of Iron containing Phosphorus.*

With regard to the influence of phosphorus on iron, it is known that even a small proportion of this element, such as 0·1 or 0·2%, will, on strong prolonged heating, impart to the metal a coarsely-crystalline texture, and by this means diminish its strength and extensibility; thus making the metal what is termed cold-short. But it is also known that if the iron after heating be drawn out to such an extent that on slow fracture it exhibits a fibrous structure, the metal becomes both strong and tenacious. If, however, an article, such as a screw-bolt, be manufactured from an iron bar which is rich in phosphorus, but which by tilting has attained the requisite degree of tenacity, the texture at the top of the bolt is often so changed by heating that it may be broken by a single blow. For the same reason a tyre which is not rolled solid, but is welded, may be sound throughout the greater part of the circumference, even if the material contain a tolerably large proportion of phosphorus; but at the welding-joint such a tyre has nearly always a coarsely-crystalline structure, and is therefore dangerous. For articles of considerable size, such as the large axles of machinery, the use of iron containing much phosphorus must be entirely avoided; for the mechanical treatment which such objects undergo is not sufficient to overcome the brittleness resulting from a coarsely-crystalline texture. Such iron may, however, be employed without any particular inconvenience for certain rolled articles which never require to be strongly heated after

leaving the mill; such, for example, as rails. Indeed, the upper part of rails, both in England and on the Continent, is usually manufactured of iron containing a large amount of phosphorus; for the phosphorus renders the iron more readily welded, and increases its stiffness and capacity of resisting wear. From this property of being weldable at a low temperature, iron containing much phosphorus is not unfrequently used for boilers, gas-pipes, &c. It is generally supposed, and apparently on good ground, that iron containing phosphorus is less subject to be attacked by rust, and that boiler-plates made of such iron are less oxidized by the flame.

10. *Employment of Iron containing Slag or Cinder.*

An intermixture of slag may, as we have seen, be useful in an iron rich in phosphorus, since it diminishes to a great extent the tendency of the metal to become cold-short. On the contrary, an iron which contains much slag cannot—or at least can only with difficulty—be forged and worked hot without cracking. Such iron cannot therefore be advantageously employed for any purpose in which it is necessary to fashion the article by forging, as is the case with most of the iron required for building structures, rails, T-iron, and many other forms of worked metal. In consequence of insufficient connection between the different layers of metal which are partially separated by the intermixed cinder, such iron often exhibits seams along which it splits at ordinary temperatures on exposure to any powerful pressure, as may often be observed in rails and tyres. Iron rich in slag is also less suitable for objects which are to be coated with other metals; and it is likewise more readily attacked by water, especially if the water be saline: on this point, however, the author is not aware that any accurate comparative experiments have been undertaken.

11. *Advantages of a pure Iron for General Forgings.*

As often noticed in this memoir, there are several qualities, beyond those brought under notice in experiments on tension, which determine the value of an iron and its application to different purposes. In the choice of a material for many parts of machinery, certain kinds of smiths'-work, &c., the strength of the iron is often of comparatively small importance —the more so as this may not unfrequently be raised by suitable mechanical treatment. But in general the points which demand first attention are the soundness of the iron and its freedom as far as possible from prejudicial impurities—especially slag, sulphur, and phosphorus—so that the iron may be readily worked hot without cracking, and may not become brittle on cooling. For many such purposes, a pure iron carefully refined in the charcoal hearth must still retain the position which it has justly acquired, and will withstand competition even against the best puddled iron.[5]

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[5] Iron manufactured by the puddling process, as well as that made in the charcoal hearth, can hardly be compared in respect of purity with that made by the Bessemer process; and as there is no difficulty in producing as soft an iron by that method as by the others, and at no greater cost, such iron will in all probability take the lead whenever the pig-iron employed is suitable for its production.—*Translator.*

CHAPTER III.

EXPERIMENTS ON TENSION AT LOW AND HIGH TEMPERATURES.

1. *Introduction.*

IT has long been a common opinion that steel and iron become brittle and weak at low temperatures. Observation has shown that chains employed for capstans are more often broken during the severe cold of winter than at other seasons; and a similar remark applies to common carriage-axles, and with especial force to the axles and tyres of railway carriages. The only reliable experiments with which we are acquainted, on the behaviour of iron and steel when stretched at low temperatures, are those of Wertheim,[1] but these seem to lend no support to the general opinion above expressed. Wertheim's experiments, however, were made only with fine iron wire of 0·27, and with blue-tempered steel wire of 0·2 line diameter; and the temperature at which he examined them was in general not lower than about 14° Fahr., and in only one out of his six experiments did it sink to 7° Fahr. We have therefore considered it of interest to examine the absolute strength of rolled and forged bars of iron and steel, as well as their extensibility, limit of elasticity, and modulus of elasticity, at the lowest temperatures which occur in Sweden.

[1] Poggendorff's 'Annalen. Ergänzungsband II.'

In order to ascertain more accurately the influence of temperature on the mechanical properties of iron and steel, we have also undertaken experiments on traction at high temperatures, varying from 248° to 392° Fahr.

Before describing the apparatus employed in these investigations it should be mentioned, that it was necessary to construct that apparatus in such a manner that it might be adapted to the hydraulic stretching machine, which was placed at our disposal, and which has been previously described.

2. *Experiments on Tensile Strength in extreme Cold: Description of the Apparatus employed.*

The apparatus employed in experiments on fracture by tension at low temperatures is represented one-eighth of its natural size, in figs. 1, 2, and 3, Pl. VI. Fig. 1 is a plan of the apparatus as arranged for use; fig. 2 is a longitudinal section along the line X Y; and fig. 3 a transverse section along the dotted line U V in fig. 1. To produce the requisite reduction of temperature, we have always employed a so-called intermittent freezing machine after Carré's construction, such as is described in *Dingler's Polytechnisches Journal* for 1861, and in several other technological journals. It consists of two thick iron reservoirs, A and B, connected by a tube *c*. The cistern B is formed of an external conical vessel *a*, in which a cylinder *b* is fastened both above and below. The upper end of this cylinder is entirely open, whilst the lower end is pierced by an aperture furnished with a short tube *e*. To avoid fracture of the tube *c*, by which A is brought into connection with the space between *a* and *b*, it is fastened to A by a short tube *d*, the only use of which is to strengthen the machine. Before the apparatus is used, the vessel A is filled to about three-fourths of its capacity with strong caustic ammonia, whilst the space between *a* and *b* remains empty. The other portions of the apparatus are vacuous, and the whole is closed air-tight. When a low temperature is to be produced, the vessel B is depressed into a cistern of cold water (the

colder the better), whilst A is gradually heated in a small furnace until its temperature reaches 266° or 284° Fahr., as indicated by a thermometer placed in a small tube previously filled with oil, *y*, fig. 1. It is well known that water at 60° Fahr., and under ordinary atmospheric pressure, absorbs about 460 times its vol. of ammoniacal gas; and it is unnecessary to remark that the caustic ammonia is nothing more than water saturated with gaseous ammonia. By heating the caustic ammonia in the vessel A, the gas is expelled from solution; and as the apparatus is perfectly closed, the pressure increases, and the gas becomes condensed to the state of liquid in the cooled annular space in B. When the temperature in A has reached 266° Fahr., A contains only water, whilst B contains condensed ammonia nearly free from water. The pressure in the apparatus may amount to from 6 to 10 atmospheres, according to the temperature of the cold water. The temperature in the vessel B is of course always rather higher than that of the cooled water, and the pressure of the condensed ammonia is at 32° Fahr. = 4·4; at 50° = 6; at 66° = 7·6; and at 82° = 10 atmospheres. The vessel A is now depressed in the reservoir of cold water, from which B is removed, as shown in fig. 3. When the water in A is thus cooled it re-absorbs the ammoniacal gas with avidity; and as this absorption proceeds, the condensed ammonia evaporates in the same proportion from B. This evaporation causes a great reduction of temperature in B; and in some of the experiments, when the cylinder *b* was filled with alcohol previously cooled several degrees below 32° F., and was not connected with any other vessel, this reduction of temperature was as low as − 58° Fahr. In order to prevent B from becoming warm on removal from the reservoir of cold water in which A is afterwards immersed, the vessel B should be wrapped in cotton wadding. With a freezing apparatus of such a size as that represented in the plate, it requires one hour, or an hour and a half, for the vessel A to reach the requisite temperature of 266° Fahr., and the production of cold in B requires almost an equal length of time.

By means of the apparatus figured, a sufficient reduction of temperature was effected for all experiments on fracture by tension; but for the determination of the limit of elasticity and modulus of elasticity at low temperatures, two freezing machines have in general been employed consecutively—one of the size represented in Pl. VI., and the other somewhat smaller. This arrangement was necessary in order to obtain a sufficiently low temperature in the larger body of alcohol necessarily used for these latter researches.

In the author's latest investigations he has employed a larger freezing machine, which, according to the maker's statement, is estimated to produce two kilogrammes of ice at each operation; and by this machine there has been no difficulty in obtaining as low a temperature as $-22°$ Fahr., and even lower.

In using these machines it is of great importance to so adjust the apparatus after each operation that the vessels A and B are horizontal, and B placed above A, in which position they should remain for at least a quarter of an hour before being again employed. After each experiment, B always contains a little caustic ammonia; and if this does not run over into A, so that B is as dry as possible, only a slight degree of cold is produced. To accelerate the drying of B, it is desirable to place it for a quarter of an hour in warm water before proceeding with the experiment.

The apparatus in which the sample-bars were enclosed and cooled, during the experiments on fracture by tension at low temperatures, is represented in the figs. by D. It consists essentially of a brass tube, about two inches in diameter, terminated at one extremity by a short tube *h*, and at the other by a longer tube *i*,[2] which, like *h*, has a diameter only just large enough to admit the thick end of the sample-bar. *k* and *l* are

[2] In experiments on tension at low temperatures it was not necessary that the tube *i* should be longer than *h*; it was, however, made of the length indicated in the fig. because we required to use it afterwards in experiments at a high temperature; and for that purpose, as will afterwards appear, there is an advantage in having the tube *i* longer.

two curved copper tubes communicating with the freezing apparatus—*k* with the upper part, and *l* with the lower part. The connection between *k* and *b* was effected by a short india-rubber tube, and by two copper tubes, *m* and *q*, united by caoutchouc: the tube *q* passes into the cylinder *b* through a loose cover *u*, consisting of two semicircular halves. In *m* are soldered two smaller tubes, of which one *n* receives a thermometer, whilst the other *o* communicates with a small glass tube through the bulb *p*.

The tube *l* is connected with the cylinder *b* by means of two india-rubber tubes *r* and *t*, and a branch tube *s*.

The sample-bar is inserted in the apparatus and secured in the press as afterwards explained, and the vessel A, having been previously heated to the proper temperature, is immersed in the cistern of water C; the caoutchouc tube *t* is fastened to the small tube *e* connected with the bottom of *b*. A small pumping apparatus E is introduced into the cylinder *b*; and the tube *q* passing through the cover *u*, as well as the cylinder *b*, and the system of tubes connected therewith, are all filled with alcohol.[3] By suction through an india-rubber tube attached to *p*, the upper series of tubes, *k*, *m*, *o*, *p*, and *q*, become filled with spirit until it rises in the glass-bulb *p*, and the caoutchouc tube is then closed by a small clamp.

At the conclusion of each experiment the spirit is run off through an india-rubber tube which is connected with *s*, and is kept closed during the investigation by means of a clamp.

To protect the tube D from the effects of heat, it is surrounded by a hood of sheet zinc *v*,[4] consisting of four separate parts; and this again is surrounded by a thick external coating of cotton wadding.

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[3] Brandy containing 50% vol. of alcohol, cannot be used for this purpose if the temperature is reduced below − 27° Fahr., since brandy of that strength begins to freeze at this temperature.

[4] This hood might certainly be dispensed with in experiments on fracture by tension at low temperatures; but it is necessary if the same apparatus is to be employed for experiments at a high temperature.

All the connecting tubes should likewise be protected from heat by being well wrapped in cotton wadding, or in some other bad conductor of heat.

By the great reduction of temperature produced in B, a circulation of the spirit is spontaneously set up in the direction indicated by the arrows in fig. 3. But in order to accelerate this circulation, a pumping apparatus E is introduced into the cylinder *b*, the piston of which does not fit close to the walls, and can therefore be easily moved, and is furnished with two large tin-plate clacks. If, in consequence of violent pumping, or of any small defects in the joints of the upper tubing, air should enter the apparatus so that the spirit sinks in the bulb *p*, it must be refilled by suction in order to be certain that the circulation is not interrupted. A thermometer in the tube *n* serves to indicate the temperature to which the sample-bar is exposed. The tube D is furnished with two small tubes *x*, *x*, for the reception of thermometers; but as these would be in danger of being broken on fracture of the bar, they are only occasionally employed for controlling the indications of the instrument in *n*. Spirit thermometers must of course be employed whenever the temperature falls below, or even approaches, the freezing-point of mercury.

3. *Condition of the Sample-bars used in Experiments on Tension at Low Temperatures.*

In all the experiments on fracture by tension at low temperatures, the sample-bars have been each about 3 feet long, and filed square for a length of about 6 inches in the middle of that part which is enclosed in the tube D, so that by thus being weakened the bar would not break at any other part where it was warmer. The square portion of the sample has been divided by transverse lines into tenths of an inch, and some into twentieths, by means of the screw-measure previously described, and which has also been employed during filing to secure uniformity of dimensions. The bars have

always been fastened in the stretching-apparatus by the previously described method of stubbing at both ends, with the use of a screw at one end and a nut at the other, as shown in fig. 2; or with nuts at both ends, when more convenient.

The sample-bar and the tubes *b* and *c* have been tightened together by means of thin india-rubber tubing, stretched at one end over *b* or *c*. When soft iron is to be broken, one of these must be of such a length and so adjusted that it permits the bar to elongate at least 1 dec. inch.

When the tubular apparatus D is connected with Carré's freezing apparatus, and is filled with spirit, as previously described, pumping is commenced in E, and the temperature in D is thereby rapidly lowered. When this is sufficiently reduced, the bar is subjected to tension in the usual manner, with weights gradually increasing until the bar breaks. In these experiments the load was each time increased by a weight in the scale of the long arm of the bent lever corresponding to 10 lbs., or at most to 20 lbs., per square line of the section of the filed part of the bar. When the bar had been broken and removed from the apparatus, its elongation between the divisional marks drawn upon it, as well as the area of its fractured surface, was measured.

4. *Comparative Experiments on Tensile Strength at about* 60° *Fahr. (ordinary temperature).*

In order to make these experiments as valuable as possible with regard to the influence of temperature on the strength and extensibility of iron and steel, the sample-bar, when its original length was 6 feet, has usually been divided into two parts each 3 feet long: one of these halves has then been strained at a low temperature, and the other at about 59° Fahr. When the original length of the sample-bar was so great that it gave more than two 3-feet bars, one at least of these has been tested at 60° Fahr. This method certainly occupies considerable time, but it was deemed necessary,

because in many kinds of iron and steel, separate bars of the same make present great differences with regard to strength and extensibility; but it may be fairly assumed that the same bar if carefully manufactured will be nearly homogeneous throughout—an assumption which experiment has indeed confirmed. Excepting some bars of hard and very slightly extensible steel, all bars which were broken at 60° Fahr. were surrounded during the experiment by water of that temperature. For when the stretching begins to produce a permanent elongation, it raises the temperature of the bars, especially those of soft iron; and therefore if the tension were effected in the open air, it would be impossible to determine the temperature of the bar from that of the atmosphere, as the former might be considerably higher than the latter.

5. *Experiments on Tensile Strength at High Temperatures.*

As a knowledge of the absolute strength and extensibility of iron and steel at temperatures of from 212° to 392° Fahr. is of great practical importance in many cases,—as, for example, with regard to their employment for boilers,—investigations have also been undertaken on this subject; and these experiments have for the most part been conducted in a similar way to those at very low temperatures. Each of the sample-bars has been about 3 feet long, and filed in the middle for a length of about 6 inches, to ensure fracture at that part. In order to expose them to a suitable degree of heat, they have been introduced into the previously-described apparatus used in experiments on tension at low temperatures, and represented in figs. 1 to 4, Pl. VI. In this case, however, the sample-bars have been surrounded by melted paraffine, which, in consequence of its thin consistence, seemed well adapted to this purpose. The paraffine is heated in a cylindrical copper vessel, communicating by means of copper tubes with the apparatus that surrounds the sample-bar. In fig. 4, Pl. VI., A represents this copper reservoir surrounded by an external covering B; C is the pumping arrangement by which

the circulation of the hot paraffine is accelerated, so that the bar may be surrounded by liquid of a nearly uniform temperature; and D is the tubular apparatus which encloses the sample-bar, and is itself surrounded by a hood of sheet-zinc to prevent loss of heat. The hot paraffine is forced in from below through the tubes *a* and *l*, and makes its exit from above through *k* and *b*. *x x* are two short tubes in which thermometers may be inserted; and the tube *c* in the cylinder A answers a similar purpose. When, however, it is apprehended that the bar is about to break, the thermometers must be drawn up some distance in the tubes *x x*; but as they are in great danger when in this position of being injured through the shock which the whole apparatus receives on fracture of the bar, we have generally preferred to use only one thermometer, placed in the tube *c* connected with the cylinder A; especially as its indications, on steady pumping, have proved to be only 1 or 2 degrees higher than those of the thermometers in *x x*—a difference which of course is of no importance in such experiments.

The sample-bar may be fastened tight in the tubes *h*, *i*, (fig. 2), by binding india-rubber tubing over the bar and the tubes, as in experiments at low temperatures. The india-rubber tube at *h* was thick, in order the better to resist the action of the paraffine, whilst that at the end of *i* was thin and pressed together, so that it lay in folds and thus opposed no great resistance to the elongation of the bar.

As melted paraffine attacks vulcanized india-rubber, even at a temperature of only 266° or 302° Fahr., we have endeavoured to keep the copper tube *i* cooler, and thus protect the india-rubber tubing, partly by making the tube *i* longer than the corresponding tube at the other end, and partly by retarding the circulation of the paraffine in *i* by surrounding the sample-bar with a short india-rubber tube, which nearly filled the space between the bar and the copper tube.

The junctions between the tubes *a* and *l*, and *b* and *k*, were made with stout caoutchouc tubing; and when a higher temperature than 320° Fahr. was employed, this tubing was bound

round with annealed brass or iron wire. The flanges of *a* and *b*, and the short tube on the cylinder A, were secured by intermediate rings of copper softened by annealing.

The entire tubular apparatus was suspended and counterpoised, so that it might not press on the sample-bar, as in experiments at low temperatures.

In order that the bar when raised by stretching might not receive any lateral pressure from the connection of the cylinder A with the apparatus, this cylinder was fixed by iron wires *e*, *e*, to the taps *d*, *d* on the upper part of the cylinder, so that it might swing freely in the casing B.

The paraffine was of course first melted in a separate vessel, and heated to the requisite temperature. It was afterwards maintained at this temperature, or raised, according to circumstances, by means of a gas-lamp placed under the cylinder A, and consisting of three large Elsner's burners, each having its own cock. After each experiment, the paraffine is run off through the tap on the tube *a*.

At a high temperature, paraffine, as previously noticed, energetically attacks india-rubber; and therefore in some of the experiments on fracture the sample-bar was enclosed in a tube of cast-iron, heated directly by means of such a gas-apparatus as that employed in organic analysis. This iron tube is represented in Pl. II., where fig. 5 shows a front view, and fig. 6 an end view. In these figures, *a a* are short tubes over which india-rubber tubing is stretched to impede the circulation of air; and *b*, *b*, *b*, are three tubes for the reception of thermometers. When the gas-burners are so regulated that the necessary heat is attained, and when the three thermometers show nearly the same temperature and this remains tolerably constant, the thermometers should be removed, and used only now and then to observe whether the temperature around the bar has undergone any essential alteration. When the thermometers are allowed to remain in the apparatus during the fracture of the bar, they ought at least to be drawn up in the tubes and protected by caoutchouc tubing, so that they may not be dashed against the sides of the

tubes on the concussion which accompanies the rupture of the bar.

6. *Results of Experiments on Tensile Strength at different Temperatures.*

The results of all these experiments on fracture at high and low temperatures are collected in Table VII., for comparison with those obtained at the ordinary temperature.

In this table we have given, as a measure of extensibility, the percentage elongation after fracture, calculated partly on the measured and divided portion of the bar at which fracture did not occur, and partly on the entire length of the divided portion, if the bar was not ruptured beyond the outer divisions. This has not, however, been always of the same length, but in very hard bars, difficult to file, it has been sometimes only 3·5 or 4 inches, instead of the usual length of 4·5 inches. In order, therefore, to make the elongations in such cases as far as possible comparable with those of other bars measured after fracture, we have calculated the percentage elongation which would have been obtained if the divided portion of the bar had originally been 4·5 inches in length. This elongation is always greatest at the inch-division where fracture occurs, and of course the elongation at that part will increase the percentage elongation the more, the shorter the divided length may be.

From this table it is seen that among all the bars broken at very low temperatures only one—namely, the cast-steel bar No. 18—broke with a smaller load than was necessary to fracture another portion of the same bar at the ordinary temperature. In this case, however, the difference between the two breaking weights is too insignificant to demand attention; and, moreover, an opposite result was obtained with another bar of the same make, No. 20. In general, the extensibility has not been found less at low than at ordinary temperatures.

On the contrary, at higher temperatures, between 212° and 392° Fahr., the absolute strength of iron is considerably

greater than at ordinary temperatures, as Dr. Fairbairn also found in his experiments; but on the other hand the extensibility appears to be somewhat diminished. In steel, however, there does not seem to be any essential difference, either in absolute strength or in extensibility, within the range of temperature mentioned.

The greatest increase of strength by elevation of temperature was found in those kinds of iron which contained but little carbon; and in order to ascertain that this result was not accidentally occasioned by the filed portions of the bars having been harder than the rest, we determined the amount of carbon at the place of fracture in the bar numbered 71 in Table VII., this bar having been ruptured in a paraffine bath. The proportion of carbon in that part was found to be 0·07%, and therefore was not greater than in other bars of the same kind of iron. From this experiment, as well as from those performed in hot air with the cast-iron apparatus represented in Pl. II., it is manifest that the increased strength exhibited by iron at high temperatures cannot be referable to any chemical influence, or carburization, exerted by the paraffine on the iron during the experiment.[5]

As it is well known that the specific gravity of iron is diminished by stretching at ordinary temperatures, we considered it would be of interest to determine whether the same effect is produced, and if so in what manner, when the traction is performed at other temperatures. For this purpose we have taken the specific gravities of some of the bars mentioned in Table VII. after fracture, examining both the filed portion and the original unfiled part, which in general has not suffered any perceptible alteration by

[5] It is indeed highly improbable that paraffine, at so low a temperature and in so short a time as that required for these experiments—the time rarely exceeding one hour—would be able to carburize an iron bar. Nevertheless, the French metallurgist Chenot asserts that reduced iron in a spongy state, if left in oil, becomes *at the ordinary temperature* cemented and converted into steel. This experiment, however, has not, as far as the author knows, been confirmed by any other observer.

stretching. It was believed that from these determinations some explanation might possibly be found of the very remarkable quality which iron possesses of becoming stronger at certain degrees of heat than at ordinary temperatures. As seen, however, from Table VII., there is generally no great difference between the diminutions of specific gravity when the fracture by extension was performed at different degrees of temperature.

7. *Experiments on the Modulus and Limit of Elasticity in Iron and Steel at different Temperatures: Description of Apparatus employed.*

Experiments have also been made in order to determine in what manner the position of the limit of elasticity, and the value of the modulus of elasticity in iron and steel, are dependent on the temperature at which the tension is performed. The bars used for these experiments were each about 6 feet long, and were inserted in the apparatus previously described and figured in figs. 1 to 4, Pl. VII. This apparatus, as already stated, consists essentially of a brass tube A about 4·76 feet long and 2 inches wide. At the lower part of this tube a smaller parallel tube B is inserted at each end, and from the middle project two bent tubes D and E. During experiments in severe cold, D is connected by tubes with the upper part of Carré's freezing apparatus, and a tube C soldered on to B is connected with the lower part, in essentially the same manner as that shown in fig. 3, Pl. VI. When the apparatus is in action, a stream of cold spirit flows from the bottom of the cylinder *b* through the india-rubber tube into C, where it is divided into two streams, one of which passes to each end of the large tube A. It thus enters at the lower side, but makes its exit at the middle of the upper part through D, returning by the connecting tubes to the upper portion of the freezing apparatus. Two small tubes, *c*, *c*, are soldered on to A, for the reception of two thermometers, the bulbs of which may be

depressed, if desirable, nearly to the bottom of A, as the tubes, *c, c*, are placed on one side of the vertical plane passing through the axis of A. The tubular apparatus is also surrounded, as in the experiments on fracture, by a zinc hood, on the outside of which is a thick coating of cotton wadding, which it was unnecessary to show in the figure. When the pump placed in the cooling apparatus has been worked for about a quarter of an hour, the temperature around the bar becomes quite uniform, if the apparatus is well protected; and the thermometer in the middle of the tube A stands only 0·1° or 0·3° higher than those at the two ends of A where the streams of cold spirit enter.

In order that the apparatus when filled with spirit may not press on the bar under test, it has always, as in other experiments, been suspended by cords from two balances, about one foot long, placed in a frame above, and so counterpoised that if the nuts to the screws *k, k*, (fig. 2, Pl. I.) are loosened, the bar moves freely in the apertures of the cross-pieces *h* and *i* (figs. 3 and 4, Pl. I.).

In experiments at high temperatures the tubes C and E (of which the latter is bent into an S-shape, and is of an elliptical section in order to be the more easily bent), are united by thick india-rubber tubing with the tubes *a* and *b*, which proceed from the copper vessel A, shown in figs. 4 and 5, Pl. VI. When the entire apparatus is filled with hot paraffine, it is forced by the pump C, placed in A, through the tube *a* (fig. 4, Pl. VI.) into B, where it is divided into two streams, which enter A at the lower side near the two ends. As the paraffine cools down, it falls to the bottom, and therefore makes its exit at the lower side of A through the tube E, and returns by *b* (fig. 4, Pl. VI.) to the copper reservoir above described, where it is heated afresh. The tubular apparatus surrounding the sample-bar is of course encased during these experiments by the zinc covering coated with cotton wadding. When the paraffine has been kept in continual motion by the pumping-machine C, and the apparatus has been coated in the manner just described,

the thermometers inserted in the extremities of A rarely differ in their indications more than 0·1°. When the pumping has been continued for about a quarter of an hour, the middle thermometer has not generally deviated from those at the ends by more than 0·5°. At temperatures above 302° Fahr. paraffine rapidly corrodes thin india-rubber tubing, and, therefore, in these experiments the temperature has rarely been allowed to rise higher than that point.

In the middle of the tube A, figs. 1 and 2, Pl. VII., is fixed the arrangement previously described by which the position of the sample-bar may be so adjusted that the extending forces, as far as possible, shall act centrally; and the necessary correction may be made for the different curvatures of the bar on different occasions.[6] The formula for these corrections, as well as for those of temperature, is found to be as follows—when the plane of the scale, as was usually the case, lay about 3·6 lines above the axis of the bars—viz.:—

$$L' - L = l_1 - l_0 + 0{\cdot}064\,(x_1 + y_1 - x_0 - y_0) - 7248\,\delta\,(t_1 - t_0).$$

Partly, and indeed chiefly, on the ground of certain well-known experiments on the coefficients of expansion of steel

[6] By the side of the tubes *e*, *e*, (figs. 1 to 4, Pl. VII.), and parallel with them are two large tubes *l*, *l*, in which are placed two bars *m*, *m*, bent rectangular at their lower extremities. The object of these bars is to receive the sample-bar below and raise it until it touches the bars *d*, *d*, adjusted at a preceding experiment and fastened by screws, so that the middle of the bar is brought into precisely the same position as it had in the previous experiment. The bars *m*, *m*, when they have raised the bar, must of course be secured, which is accomplished by small cods so screwed on to the tops that they touch the boxes on the upper part of the tubes *l*, *l*. If the length of the sample-bar should be measured when set free as previously indicated, which may be especially needful when the lever is loaded with weights troublesome to remove, we can thus bring the middle of the bar into the same position which it occupied at the preceding measurement, when the bar was extended by so great a force that it was kept nearly straight. As, however, it was found that even with the use of the hooks the length of the free bar could not be measured with the same accuracy as the length of the bar when stretched by a moderate force, these hooks have but rarely been employed; and indeed such a degree of accuracy has never been requisite.

and iron, and partly also on the ground of special experiments of our own, in which the length of several bars placed in our apparatus, and stretched by a suitable weight, was accurately measured at differences of temperature of from 9° to 18° Fahr., we have found it necessary to give the following values to the coefficient of $t_1 - t_0$ in the formula above, viz.:—

			$7 \cdot 248\ \delta =$
For steel at about	− 13° Fahr.,	.. ..	0·065
Do.	+ 59° ,,	.. ..	0·078
Do.	+266° ,,	.. ..	0·088
For iron at about	− 13° ,,	.. ..	0·072
Do.	+ 59° ,,	.. ..	0·085
Do.	+266° ,,	.. ..	0·095

The coefficient of expansion certainly seems to be lowered in steel as the amount of carbon is increased; but as the difference of temperature at two successive extensions has rarely been more than 0·5°, it has not been considered necessary to notice this circumstance. The temperature of the sample-bars is, moreover, not indicated precisely by the thermometers, and, therefore, the corrected measurements of length always showed the best agreement when the temperature could be maintained nearly constant.

In all these researches the instrument employed for measuring the elongations has been wrapped in cotton wadding and calico, in order that it might not be affected by the temperature of the apparatus. In this way the instrument has been so well protected, that thermometers placed in cotton have rarely been raised or lowered more than 1° during a series of experiments continued for several hours. Under these conditions it is certain, that the length of the measuring instrument could not have been perceptibly changed during the short time which elapsed between the successive observations of length—a point which, of course, is of the greatest importance in the determination of the modulus of elasticity.

8. *Experiments on the Position of the Limit of Elasticity at different Temperatures.*

As, in these experiments, the temperature at those parts of the sample-bars which lie between the branches of the tube A and the fixed points of the scale might differ to a considerable extent from that of the part within the tube A,[7] it was considered necessary in experiments on the limit of elasticity to prevent permanent elongation in those portions. In researches on the limit of elasticity we have, therefore, used only such bars as have been filed down for a length of about 4·5 feet, so that the section at that part, even if previously round, has become nearly square, and in general about 33% less than the section of the other part. These bars have been so fastened in the apparatus that the filed portion has been quite enclosed within the tube A (figs. 1 and 2, Pl. VII.), and its ends have been at nearly equal distances from the branches of the tube. There was special necessity for this precaution, as it had been previously found by ex-

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[7] In order to obtain approximately an idea of the temperature that prevailed in these parts of the sample-bar, wires of German silver and iron were soldered on to the bar at the lines which were marked at a distance of 5 feet apart, and therefore at the fixed points of the scales. The other ends of these silver-wires were soldered to other iron-wires, and had their junction placed in a bath of cold spirit or hot paraffine, the temperature of which could be accurately regulated and measured. When the iron-wires were connected with a galvanometer, the temperature could be determined with sufficient accuracy in the manner of a thermo-electric arrangement. In this way we found that when one of the fixed points of the scale was 1·744 inch outside the branch of the tube A, and the temperature within this tube was 25° Fahr., then the temperature at the fixed point of the scale was 23° Fahr.; and when at the former place it was 278° Fahr., it was only 168° Fahr. at the latter; whilst in both cases the temperature within the tube was maintained nearly constant for at least a quarter of an hour.

By soldering wires of German silver and iron at the junction between the filed and unfiled portions of a sample-bar, we found in the same way that when the bar was heated in a paraffine bath of about 284° Fahr., and the junction referred to was placed about 1·166 inch within the branches of the tube A, the temperature at that point was not more than 0·3 of a degree lower than that indicated by the thermometer placed within the tube. It may therefore be considered, that the thermometers in A generally indicated with sufficient accuracy the mean temperature at the filed part of the sample-bar.

periments on flexion that the limit of elasticity in both iron and steel is higher at very low than at ordinary temperatures.[8]

The position of the limit of elasticity in iron and steel is in a great measure dependent, as previously proved, on the mechanical treatment to which the material has been subjected, and on the temperature to which it has been subsequently exposed. This limit can never, therefore, be known with accuracy without a special determination, and by such a determination the limit itself is raised. It has been found that with a bar which has been extended beyond its limit of elasticity, the position of the new limit might, *under ordinary conditions*, be easily determined by representing the permanent elongations graphically; for, as explained on p. 37, the upper parts of the curves for a new series of experiments at the same temperature will lie in the continuation of the preceding curves. It was therefore supposed, at the commencement of these experiments, that by taking advantage of this circumstance it would be possible to determine with sufficient accuracy the dependence of the limit of elasticity

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[8] These experiments were undertaken with steel and iron wires, of about ⅛ inch diameter, which were inserted in the axis of the cylinder *b* in Carré's freezing apparatus, and were fastened by a kind of screw to the lower part of the reservoir B, whilst the upper end was fastened to an iron axis. This was placed in a brass fastening in the centre of a wooden cover attached to the cylinder *b*, and moveable by means of a handle. The cylinder *b* was for the most part filled with spirit during these experiments.

It was found that as soon as any part of the silver or iron-wire was above the cold spirit, only that part which was less cold became twisted, until the wire was finally broken; but when the iron axis reached the spirit, the wire was pretty evenly twisted. By giving the wires a coating of copper on one side, it was easy to count the number of times which the wires could be twisted for a certain length before being broken. In this manner we tested some iron-wire from Lesjöforss and Gunnebo, drawn from very cold-short iron made by the Swedish finery process, containing 0·25% phosphorus, together with English cast-steel wire; and it was found that these wires could be twisted for a certain length, without breaking, about as many times at a low temperature of 22° to 40° Fahr. as at ordinary temperatures.

These preliminary experiments seemed to show that iron and steel do not, as previously imagined, become brittle at low temperatures, but retain as high a ductility and tenacity as at ordinary temperatures.

on the temperature at which the extension was performed. For such a purpose, therefore, the limit of elasticity should be determined for each bar, first, at the ordinary temperature, and then at a very low or high temperature; the curves of elongation for both series should afterwards be traced, and finally that point determined at which the tangent to the upper part of the curve of the latter series cuts the ordinate of the terminal point of the former, as shown by dotted lines in the three first curves on Pl. VIII., for the bar numbered 2 in Table VIII. The length of that portion of the ordinate lying between the tangent referred to and the end of the preceding curve, would thus measure the *temporary* elevation or depression of the limit of elasticity consequent upon the difference of temperature at the two experiments. In this manner we have found that the limit of elasticity in both steel and iron is always higher at low temperatures, and in iron is lower at high temperatures, than when the extension is performed at the ordinary temperature; but that, on the contrary, in hard steel at a heat of 266° to 302° Fahr., it is sometimes higher and sometimes lower. When the limit of elasticity in such steel has been found higher at about 284° than at about 59° Fahr., and has been again examined at the latter temperature, the result has often been somewhat higher than might have been anticipated from the experiments at high temperatures.[9] This arose from the fact afterwards observed that when a stretched bar is heated, even to so moderate a temperature as 266° or 302° Fahr., a change is effected in the molecular condition of the metal, which is retained after the heat has been removed; and therefore the limit of elasticity is often *permanently* altered. Since we know that the limit of elasticity is lowered in iron and steel by annealing, after having been previously raised by tension or other mechanical treatment, it was not expected that a moderate

[9] Compare Tab. VIII., bar No. 1, series 7 and 8, with No. 3, series 4 and 5.

heating could raise the limit any further [10] Sometimes we have even found that the limit of elasticity in stretched bars has been perceptibly raised by merely allowing the bar to remain at rest for several days after stretching. It has previously been stated that the modulus of elasticity in stretched bars of iron and steel may also be raised by remaining at rest or by exposure to a moderate heat. The metal appears to acquire by this means new strength after having suffered from overstraining. On the other hand it has not been found that by cooling to a very low temperature, any perceptible *permanent* influence has been exerted on the position of the limit of elasticity in iron and steel.

By determining in this manner the limit of elasticity at high temperatures, the temporary influence of the heat has not been ascertained distinct from its permanent influence; and therefore the results attained by the method described above do not—at least for iron—give any trustworthy *measure* of the temporary change in the limit of elasticity by heating. As, however, the subject has been but very little investigated, we have considered that the results are of sufficient importance to merit publication. In Table VIII. we have therefore given the results of the experiments with reference to the position of the limit of elasticity at very low temperatures, as well as those undertaken to determine the *permanent* influence of heating and cooling. Experiments on the limit of elasticity at different temperatures should, however, show, with at least sufficient accuracy for practical purposes, by *how much* the limit is raised in iron and steel when stretched at low temperatures, and *within what limits* it may vary when stretched at higher temperatures not exceeding 302° Fahr.[1] Some of the experiments referred to are represented graphically in Pl. VIII.

[10] Compare Tab. VIII., bar No. 1, series 2, with No. 6, series 2, and No. 9, series 7.

[1] We ought indeed to have been able to examine the variation in the position of the limit of elasticity with the temperature, by examining different portions of the same bar at different temperatures. We have not, however, had at our disposal bars which have been either long or smooth enough for such investigations.

9. *Experiments on the Variation of the Modulus of Elasticity at different Temperatures.*

In our experiments on the variation of the modulus of elasticity with the temperature, we have, as previously stated (pp. 63, 66), first determined, by several experiments at ordinary temperatures, the differences between the elastic elongations when the sample-bar has been successively stretched by properly-adapted loads, and have calculated the average of these differences corrected by the formula previously given. Similar determinations have afterwards been performed at low or at high temperatures, and been finally renewed at the ordinary temperature. If the bar has not been overstretched, either previously or during the experiment, the results of the tension at ordinary temperatures, as performed before and after heating or cooling, have nearly always shown the closest agreement; and we have then taken the average of all these, and compared it with the mean result of the experiments at high or low temperatures. If E_1 denote the modulus of elasticity at a low or high temperature, and $L_1 - L_0$ the mean value of the corrected difference between the elastic elongations obtained with the loads P_1 and P_0; and if E, $L' - L$, P' and P represent corresponding values by tension at the ordinary temperature, then we obtain

$$\frac{E_1}{E} = \frac{L' - L}{L_1 - L_0} \cdot \frac{P_1 - P_0}{P' - P},$$

or if, as usually happened,

$$P_1 - P_0 = P' - P, \text{ then } \frac{E_1}{E} = \frac{L' - L}{L' - L_0}.$$

The ratio $\frac{E_1}{E}$ is thus always independent of the section of the bar; and the accuracy with which it may be determined depends, when the extending force is alike in all the experiments, only on the accuracy with which the differences between the elastic elongations may be measured.

If the bar has been overstretched, either before or during the experiment, or if it has originally been much bent and

then straightened when cold, the experiments conducted at ordinary temperatures with the same load, *after* a series of experiments at a higher (and sometimes also after those at a lower) temperature, present less differences between the elastic elongations than are obtained from those which *precede* such a series of experiments. This results from the influence, already alluded to, which any great change of temperature exerts on overstretched bars; an influence which partially restores the elastic force which is lost by overstretching.[2]

The results of these experiments, which occupied considerable time and were attended with great practical difficulties, are given in a collected form in Table IX.

10. Résumé *of Results of Experiments on Tension at different Temperatures.*

From these experiments on tension at widely different temperatures we have thus found :—

1. That the absolute strength of iron and steel is not diminished by cold, but that even at the lowest temperature which ever occurs in Sweden, it is at least as great as at the ordinary temperature (about 60° Fahr.).
2. That at temperatures between 212° and 392° Fahr., the absolute strength of steel is nearly the same as at the ordinary temperature; but in soft iron it is always greater.
3. That neither in steel nor in iron is the extensibility

[2] Before we were aware of this circumstance we endeavoured to determine the dependence of the modulus of elasticity on temperature at the same time as we determined that of the limit of elasticity. The results obtained were, however, highly discrepant, although we never compared those series of experiments between which the bar had obtained a permanent elongation.

From the many experiments performed in this way we have obtained no result, beyond becoming acquainted with the variation in the molecular condition of stretched bars, and some of the conditions on which this variation is dependent.

less in severe cold than at the ordinary temperature; but that from 266° to 320° Fahr. it is generally diminished, not to any great extent, indeed, in steel, but considerably in iron.

4. That the limit of elasticity in both steel and iron lies higher in severe cold; but that at about 284° Fahr. it is lower, at least in iron, than at the ordinary temperature.
5. That the modulus of elasticity in both steel and iron is increased on reduction of temperature and diminished on elevation of temperature; but that these variations never exceed 0·05% for a change of temperature of 1·8° Fahr., and therefore such variations, at least for ordinary purposes, are of no special importance.

11. *Cause of frequent Fracture of certain Articles of Iron in severe Cold.*

As the results of the experiments given above are evidently opposed to the opinion hitherto commonly entertained, viz., that steel and iron become weak or brittle at low temperatures, the author may briefly state his opinion of the cause why certain articles of steel and iron break, as everybody knows, more frequently during the severe cold of winter than at other seasons. The cases on which such observations are founded are, as far as we know, chiefly those in which the objects are fastened in such a manner that they are not allowed to contract on reduction of temperature; and therefore if they become weakened at any point, as, for example, by the passage of a screw or rivet, fracture would readily occur, for reasons previously stated (pp. 76, 78), even if the articles consisted of tolerably good material. Other cases of fracture at low temperatures are presented by those objects which are exposed in the open air, and subject to constantly-recurring shocks, the intensity of which depends essentially on the greater or less rigidity or elasticity of the metal. The inconvenient effect of such shocks has been

especially observed on railways. During the severe cold of winter, not only are the sleepers hard and very slightly elastic, but the ground also—being often frozen to the depth of several feet—gives way but comparatively little,[3] so that the shocks which occur each time the carriages pass over the slightest irregularity must operate, other conditions being alike, much more violently in winter than at other seasons; and the *strain* consequently becomes considerably greater, not only on the rails, but also on the axles and wheels, and notably on the tyres, since these receive the shocks direct. It is thus evident that it is the tyres which during severe cold are most exposed to danger of being fractured.

The evil effects of a low temperature on railway traffic can, therefore, be prevented or diminished only by such means as tend to lessen the violence of the shocks to which

[3] It might be supposed that the greater or less elasticity of the ground is dependent, other conditions being alike, solely upon the depth to which it may be frozen, and is in no way affected by the number of degrees that the temperature may fall below the freezing point. Such a supposition is, however, contradicted by experience, which shows that the fracture, for example, of railway tyres and axles, usually occurs when the cold is most severe.

In order to determine how the elasticity of damp wood is affected by temperatures below 32° Fahr., a square rod of fir-wood, 4·3 feet long and about 0·625 inch thick, was kept in water until, as subsequent examination showed, it had absorbed about 50% of liquid. It was then coated with sheet gutta-percha to prevent absorption when the bar was immersed in spirit. To ascertain the amount of deflection which it suffered by the same load when exposed to different degrees of low temperature, the bar was introduced into the apparatus figured in Plate VII., to be afterwards described. In consequence of the low conducting power of wood for heat, the temperature of the interior of the bar could not be changed so rapidly as that of the spirit surrounding it; and as it could not be determined by an ordinary thermometer, a thermo-electric arrangement was employed, consisting of a pair of iron and German silver wires soldered together and inserted into the middle of the bar. If the amount of deflection by a certain load at 35° Fahr. be taken as 100, then it becomes at 29° = 97·5; at 25° = 95; at 2° F. = 88; and is thus in the last case diminished 12%.

This experiment shows that damp timber at very low temperatures yields to a considerably less extent than when the temperature is only a few degrees below 32°; and probably the same is the case with the frozen ground. *See Remarks of the Translator in the Appendix.*

the material is exposed; such, of course, as slackened speed of trains, and all means by which the rolling-stock receives greater elasticity.[4]

It has been found that axles and other iron articles, which have been tested by allowing a weight to fall upon them when laid on two supports, have resisted a smaller number of blows, or blows of less force, during severe cold than under other circumstances; and hence it has generally been concluded that iron is weaker or more brittle at low than at ordinary temperatures. It would appear, however, that in such experiments no allowance has been made for the influence of the hard frozen ground on which the supports rested, or for the special manner in which their greater or less solidity would affect the resistance offered by the given object.[5]

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[4] See the remarks of the Translator in the Appendix.

[5] *Note by Translator.*—Fully aware of the great care and accuracy with which these experiments were performed, the translator cannot entertain the slightest doubt as to the correctness of the numerical results obtained, or the validity of the conclusion drawn from them as expressed on p. 111, namely, that the absolute strength of iron and steel is not diminished by the influence of cold on the metal itself *when tested by stretching.* But when the author, as on p. 112, practically applies this new theory to the case of railway materials —such as axles, tyres, and rails,—which he admits are exposed to *blows*, and not to the action of a dead weight, and refers to the difference of elasticity in the supports (sleepers) at different seasons as the *sole* reason why such materials break more readily in winter than in summer, then the translator can by no means agree with him. On this subject the author was consulted, but as he still persisted that frost could have no effect on iron in its resistance to blows, provided that the elasticity of the supports remained constant, it became the duty of the translator, as an Inspector of railway materials for the Swedish Government, to ascertain the real position of the case by experiments of a practical nature. Accordingly, the State Railway Administration having consented, and the author having been consulted, experiments were conducted by the translator at Stockholm in the winter and summer of 1867. Iron rails were supported on blocks of granite, which in their turn rested on a solid granite rock, and the rails having been broken into halves were then tested by the fall of a heavy ball—one half of each rail being examined in winter at 10° F., and the other half in summer at 84° F. The results of these experiments showed that in the former case a rail would not sustain much more than one-fourth of the blow which it resisted at the latter temperature.

For the details of these experiments the translator must refer the reader to the Appendix.

CHAPTER IV.

EXPERIMENTS ON FLEXION AT DIFFERENT DEGREES OF TEMPERATURE.

1. Introduction. — 2. Description of the apparatus used in experiments on flexion. — 3. Experiments on the different degrees of stiffness in iron on flexion at different temperatures. — 4. Determination of the modulus of elasticity on flexion. — 5. Means by which the value of the modulus may be altered. — 6. Experiments on the influence of temperature on the modulus on flexion. — 7. *Résumé* of results.

1. *Introduction.*

As it was found, from the experiments previously described, that the modulus of elasticity on tension is nearly alike in steel and iron of the same specific gravity, but that it increases as the temperature falls, and diminishes as the temperature rises, it was considered interesting to examine the influence which these conditions would exert on flexion; because the elastic deflections may be much greater than the elastic elongations at tension, and therefore the former admit of measurement with greater accuracy.

2. *Description of Apparatus used in Experiments on Flexion.*

For this purpose we have constructed the apparatus represented in figs. 5 to 10, Pl. VII. Fig. 5 shows a front view, fig. 6 a vertical-longitudinal section through the middle of the apparatus, fig. 7 is a plan, and the remaining figures are transverse sections; fig. 8 being taken across the line X Y, and fig. 9 across U V, in fig. 5, both sections showing the parts behind; whilst fig. 10 is a section across the line W Z in fig. 7. In using this apparatus the sample-bar is enclosed in the brass tube *a*, which is about 4·3 feet long, and has a sectional form shown in figs. 8, 9, and 10. In the lower part of each extremity of this tube is inserted the end of a smaller pipe *b*, furnished near the middle with a shorter

tube *c* at a right angle. During experiments on flexion at low temperatures, this tube *c* is connected with the lower part of Carré's freezing apparatus, as previously described in experiments on tensile strength. The stream of cold spirit entering by *c* is afterwards divided into two currents, which enter *a* near its two extremities, and return to the freezing apparatus through a short tube *d*, leading from the upper side of *a*. On the contrary, in experiments on flexion at high temperatures, the tubes *c* and *d* are connected by means of stout india-rubber tubing with the tubes *a* and *b* in fig. 4, Pl. VI. The apparatus is then filled with hot paraffine, which, by means of the pumping arrangement, is forced to circulate through the apparatus, and is heated in the reservoir A. At the ends of *a* are fitted two short tubes *e*, *e*, through which the sample-bar is introduced. These are secured by thin caoutchouc tubing, as shown in figs. 5 and 7, which is fitted in such a way that the position of the bar may be regulated without emptying the apparatus. Strong iron bars, *f*, *f*, pass through the sides of the tube *a* near its extremities, and these bars are filed in the middle so that they present prismatic edges on which the sample-bar (A) rests during the experiment, as shown in fig. 6. The flexure of the bar is effected by an iron hoop *h*, in the upper part of which the steel bar *i* is securely fastened by a screw and nut. This bar *i*, which terminates below in an edge, is formed as shown in fig. 9, and during the experiment rests on the centre of the sample-bar between its two supports. It is capable of moving freely up and down in the tube *g*, which rests on the upper part of *a*. At its lower end, the hoop *h* is furnished with a hook *k*, from which is suspended a scale-pan for the reception of weights. To the upper part of the bar *i* is soldered a small silver scale, whose vertical middle line coincides with the axis of the bar *i*. The position of the hook *k*, supporting the scale-pan, should also be in the axis of the bar *i* produced.

A fine cord attached to the upper end of this small silver scale serves to attach the hoop *h*, during the experiment, to

one arm of a small balance placed above, from the other arm of which is suspended a scale-pan. By means of suitable weights placed in this scale, and on that which hangs from the hook *k*, the bar *i* may always be maintained in a vertical position, and the hoop *h* with its appurtenances may be counterpoised at pleasure. The weights have usually been so adjusted that an additional weight of 2 lbs. produced pressure on the bar. The descent of the bar by a weight was measured by a cathetometer, by which a difference of $\frac{1}{50}$ of millimètre could be read off. It is evident that both the apparatus in which the sample-bar is enclosed, and the cathetometer, must rest on perfectly solid supports. On the upper side of *a* is soldered a small iron bar *m*, the upper end of which carries a delicate index-scale, from which it may be observed by the cathetometer whether the support of the sample-bar has been perceptibly shaken or displaced between different operations. During the experiments thin india-rubber tubing is bound round the tube *g*, and tightened when the pump in the cooling apparatus or in the paraffine reservoir is actively worked, but is loosened when observations are to be made with the cathetometer. The tubes *n*, *n*, serve to receive thermometers. Under the scale-pan, suspended from the hook *k*, is placed a small round platform, which may be raised or lowered by means of a screw, so that the load may be applied without concussion.

In experiments at high and low temperatures this apparatus, like that used in researches on tension, has of course been surrounded by a coating of some badly-conducting material.

3. *Experiments on the different Degrees of Stiffness in Iron on Flexion at different Temperatures.*

Although the apparatus just described was constructed chiefly for the determination of the modulus of elasticity, it has been also used in some few experiments on variations in the stiffness of iron at different temperatures. In consequence of the small depth of the apparatus, the bars in these

experiments could obtain only a small permanent deflection, and therefore it has not been deemed necessary to give the details of these experiments. It will suffice then to state that iron on flexion was found to be stiffer in cold than at the ordinary temperature, and that the stiffness decreases as the temperature rises.

4. *Determination of the Modulus of Elasticity on Flexion.*

In the determination of the value of the modulus of elasticity on flexion, we have made use of some of the bars previously tested by stretching, as noticed in Table IX., whenever these bars have been cut to the requisite length of 4·3 feet; a length which they must possess in order to be enclosed in the apparatus shown in figs. 6 to 10, Pl. VII. Certain other bars have also been tested in these experiments, and all have been filed even with great care.

In these researches it is of even more importance than in the determination of the modulus of elasticity by tension, that the sectional area of the bar, and especially its height, be uniform and accurately measured. Hence, in these experiments, the dimensions of the sectional area have been taken by means of the screw-measure at every other inch. Indeed, the third power of the height enters into the formula for calculation of the modulus of elasticity. For perfectly regular bars with a rectangular section, the free ends of which rest on two edges in the apparatus, when the loads are applied to the middle of the bars, the formula for the modulus of elasticity becomes

$$E = \frac{P\,l^3}{4\,bh^3 f},$$

where P is the load on the middle of the bar, l the distance between the edges, b the breadth of the bar, h its height, and f the deflection of the loaded bar. It was not possible to determine accurately the position of the bar within the apparatus when slightly loaded, but only to measure the difference between the deflections with two different loads.

If the difference between these loads be denoted by p, and the difference between the corresponding deflections by d, and if we substitute for l the actual length between the edges in our apparatus, which was 46·5 inches, then the formula we employed becomes

$$E = \frac{p}{d} \cdot \frac{16,000,000}{bh^3}.$$

The results given in Table X. show (among other things) that in one and the same bar the modulus of elasticity on flexion has in general nearly the same value as that determined by stretching. In a note on p. 61 it has been already stated that perfect accordance between the moduli of elasticity on flexion and traction can be expected only under certain conditions. Moreover, it should not be forgotten that if the material throughout the sample-bar be not uniform, the relative position of the differently-constituted portions has no influence on the amount of the elastic elongations obtained by extension; but that at flexion, on the contrary, the quality of the material in the middle of the sample-bar more than at any other part affects the extent of the elastic deflections.

5. *Means by which the Value of the Modulus of Elasticity may be Altered.*

In experiments on flexion, as in those on extension, we have had opportunity to observe how the elastic force in one and the same bar may vary according to the treatment which the bar may have received. By permanent deflection the modulus is diminished; by moderate heating it is partially restored; and by a red heat it is raised to a maximum. By small permanent deflections caused by loads acting on the middle of the bar, the modulus of elasticity is slightly diminished; for by a load applied in this way the bar is bent only in the middle, the other parts remaining unchanged. But, on the other hand, if the bar by any means be bent throughout its entire length, so that a change is effected in the molecular condition of the whole, or at least the greater part of the bar, then the diminution of the

modulus of elasticity may amount to several units per cent., as found from experiments with the bar numbered 13 in Table X.

In order to show more exactly what influence moderate heating exerts on the elastic force of a bar which has received a permanent deflection, we may refer, by way of example, to certain experiments made with the bar No. 1 in Table X.

When the hoop *h* with its appurtenances had been counterpoised, as previously explained, a weight of 70 lbs. was placed in the scale-pan under the hoop, and the depression of the silver scale *l*, fastened to the upper part of the bar *i* (figs. 5, 6, and 9, Pl. VII.), was determined by means of the cathetometer. With this difference between the loads, or 70 lbs., it was found that the difference *d* between the deflections was on an average 23·65 millimètres. When the same bar was curved upwards at the middle about $\frac{3}{8}$ inch, and afterwards straightened, *d* was found to be increased to 24·415 millimètres with the same load, reckoned as the mean of several experiments. The bar was then heated for about half-an-hour in a paraffine bath at 257° Fahr., and was afterwards slowly cooled, when with the same load *d* was only 24·030 millimètres. By the violent treatment which the bar had suffered previous to heating, its elastic force had thus been diminished 3·1%, and only about one-half of this loss had been restored by heating.

With regard to the effect of annealing on the elastic force of steel and iron, it is sufficient to refer to Table X.

In order to determine the influence of hardening on the elastic force in steel, the sample-bar was examined first when it had been heated, then after hardening, and again when the hardening by heat had been neutralized. To compare the modulus of elasticity in a bar which had not been heated with the modulus in the same bar after having been hardened, would throw but little light on the effect of hardening. For the bar, in order to be hardened, must first be heated, and it would not, therefore, be possible to determine in ex-

periments on hardened bars whether the alteration in elastic force should be attributed to the hardening or to the heating, or in what manner it should be distributed between them.

6. *Experiments on the Influence of Temperature on the Modulus of Elasticity on Flexion.*

In all experiments referring to the influence of temperature on the modulus of elasticity, the bars have been tested first at the ordinary temperature, then at the higher or lower temperature, and finally again under ordinary conditions. If both series of experiments at the ordinary temperature agree in their results, it is evident that the change of temperature has not *permanently* altered the elastic force of the bar, but that the differences observed between the deflections at a high or a low temperature and at the ordinary temperature have, therefore, arisen only from the differences in the thermometric conditions during the experiment.

If E_1 and E_0 denote the values of the modulus of elasticity at two different temperatures t_1 and t_0, and if d_1 and d_0 denote the measured differences of deflection with the same load, and a the linear coefficient of expansion of the material in the tube a, then we obtain with sufficient accuracy the value of the ratio $\frac{E_1}{E_0}$, thus:—

$$\frac{E_1}{E_0} = \frac{d_0}{d_1} \{1 + a (t_1 - t_0)\}^3 = \frac{d_0}{d_1} \{1 + 3 a (t_1 - t_0)\}.$$

On the cooling of our apparatus from 59° Fahr. to − 4° Fahr., we have found the mean value of a = 0·000013, and on heating from 59° Fahr. to 266° Fahr. a = 0·00002.

The results obtained are given in Table X.[6] In these calculations no correction has been made for change of

[6] The manner in which the elastic force is dependent on temperature has also been examined by Kupffer by means of transverse vibrations. His experiments were undertaken on certain kinds of iron and steel between 59° and 2° Fahr.; and also on a Swedish and an English iron at about 212° Fahr. According to his results, the coefficient denoted by us β_1, which indicates the *percentage* value of this relation, should for a change of temperature of 1·8° Fahr. = 0·019 to 0·028 for steel, and = 0·028 to 0·036 for iron.

dimensions consequent upon change of temperature; for the measurement of the dimensions is generally taken at temperatures between 32° Fahr. and 68° Fahr., and the application of the results to particular cases would therefore have been more difficult with this correction. If a comparison be instituted between the influence of temperature on the elastic force at flexion and at traction, or in other words between the values of the coefficients β and β_1, given in Tables IX. and X., the correction referred to should in strictness be made in both cases, although β is only increased thereby about 0·001, and β_1 0·004.

7. Résumé *of Results of Experiments on Flex on.*

The results of all these experiments on flexion may be thus briefly summed up:—

1. Iron sustains at low temperatures a greater and at high temperatures a smaller load than at the ordinary temperature, before it obtains any perceptible permanent deflection.
2. The modulus of elasticity for steel and iron on flexion may, for practical purposes and without committing any considerable error, be generally assumed equal to that on traction. It is diminished by permanent deflection, but may be restored by heating, especially if raised to a red heat.
3. By hardening steel, its modulus of elasticity is diminished; but this diminution has not, in any of the hardened bars examined, amounted to more than about 3%.
4. The elastic force of steel and iron on flexion, as on traction, is increased on reduction of temperature and diminished on elevation of temperature. The amount of this increase or decrease for a change of temperature equal to 1·8° Fahr. (1° Centigrade) does not, however, in general amount to more than 0·03%, and apparently never rises to 0·05%.

TABLES

REFERRED TO IN THE FOREGOING WORK.

Table I.—Results of Experiments on the Tensile Strength at a temperature

Observer.	No. of experiment.	Description of steel or iron.	Section as to Form.	Section as to Mean area.	Load applied per sq. in. of mean area.	Weight laid on per sq. in. at the limit of elasticity after Wertheim's definition.	Weight per sq. in. at the maximum curvature.[1]
—	—	—	—	sq. in.	lbs.	lbs.	lbs.
Thalén	1[4]	N.H. 1	Square.	0·2343	11,116	32,868	41,172
Cronstrand ..	2[4]	,,	Round.	0·1934	—	—	43,916
Thalén	3[4]	N.P. 1	Square.	0·2316	12,214	45,289	56,954
Cronstrand ..	4[4]	,,	Round.	0·1913	—	—	57,640
Thalén	5	N. 1	Square.	0·2328	11,185	37,123	39,799
,, ...	6	,,	,,	0·2353	—	—	38,427
,, ...	7[4]	B. 1	,,	0·2332	11,185	37,054	41,858
,, ...	8[4]	,,	Round.	0·1952	13,312	27,585	43,916
Cronstrand ..	9[4]	,,	,,	0·1940	—	—	43,916
Thalén	10	P. 1	Square.	0·2328	11,116	37,054	41,858
,, ...	11	,,	,,	0·2351	—	—	39,113
,, ...	12	G. 1	,,	0·2324	11,116	37,054	39,799
,, ...	13[4]	,,	Round.	0·1899	13,724	40,554	43,230
,, ...	14[4]	N.H. 2	Square.	0·2362	10,979	30,673	38,427
,, ...	15[4]	,,	,,	0·2367	—	—	36,368
Cronstrand ..	16	,,	Round.	0·1925	—	—	41,172
Thalén	17[4]	N.P. 2	Square.	0·2367	10,979	32,535	43,230
,, ...	18	,,	,,	0·2343	—	—	45,975
Cronstrand ..	19	,,	Round.	0·1940	—	—	45,289
Thalén	20[4]	N. 2	Square.	0·2336	11,116	33,006	37,741
,, ...	21[4]	,,	,,	0·2328	—	—	34,996
Cronstrand ..	22	,,	Round.	0·1913	—	—	39,113
Thalén	23[4]	B. 2	Square.	0·2324	11,185	29,163	39,799
,, ...	24[4]	,,	Round.	0·1846	10,293	29,094	41,172
,, ...	25	P. 2	Square.	0·2324	11,185	27,173	39,799
,, ...	26[4]	,,	Round.	0·1913	16,949	34,378	41,172
,, ...	27	,,	,,	0·1949	—	—	41,858
,, ...	28	G. 2	Square.	0·2399	10,841	34,035	43,230
,, ...	29[4]	N.H. 3	,,	0·2362	7,067	30,673	34,996
Cronstrand ..	30	,,	Round.	0·1899	—	—	37,054

[1] What is meant by maximum curvature is explained p. 17. Comp. pp. 27, 28, and 33.
[2] The elongation on the foot-division at which the fracture occurred is not reckoned. Comp. note on p. 16.
[3] Comp. p. 10.

of Puddled Steel and Puddled Iron from Surahammar (Sweden) of about 60° Fahr.

Breaking weight per sq. in. on original mean area.		Section at fracture.	Breaking weight per sq. in. on section of fracture.	Ratio between the loads at fracture and at maximum curvature.	Ratio between the area of fracture and original area.	Elongation after rupture.[2]	Number of clamps used in the experiment.[3]
lbs.	tons.[5]	sq. in.	lbs.	—	—	per cent.	—
85,187	38·02	0·1613	117,065	2·07	0·73	6·06	—
86,804	38·75	—	—	1·98	—	7·37	—
98,538	43·99	0·1562	146,023	1·73	0·67	3·00	—
111,987	49·99	—	—	1·94	—	8·98	2
85,706	38·26	—	—	2·15	—	7·20	2
76,854	34·30	—	—	2·00	—	10·87	2
88,725	39·60	0·1752	118,095	2·12	0·75	4·56	—
85,021	37·95	0·1376	120,633	1·93	0·70	3·85	—
89,411	39·91	0·1784	97,234	2·03	0·92	5·98	1
93,666	41·81	0·1722	126,603	2·24	0·74	6·95	—
80,302	35·84	—	—	2·07	—	5·99	1
85,843	38·32	0·1800	110,752	2·15	0·77	5·65	2
79,599	35·71	0·1264	119,604	1·84	0·66	4·83	—
79,736	35·59	0·1608	117,065	2·07	0·68	8·23	—
74,795	33·39	—	—	2·06	—	5·71	—
81,583	36·42	0·1376	113,840	1·97	0·71	11·74	2
87,078	38·87	0·1656	120,408	2·01	0·70	5·63	—
98,606	44·02	0·2001	115,281	2·14	0·85	8·30	2
97,097	43·79	0·1492	126,192	2·14	0·77	8·70	2
76,648	34·21	0·1951	91,676	2·17	0·83	6·70	—
76,854	34·30	0·1851	96,754	2·20	0·79	8·01	—
78,072	34·85	0·1453	102,724	2·00	0·76	9·36	2
84,196	37·58	0·1579	123,721	2·11	0·68	8·91	1
75,815	33·84	0·1030	110,546	1·89	0·70	3·98	—
85,021	37·95	0·1608	122,829	2·14	0·69	6·47	—
75,138	33·54	—	—	1·82	—	4·08	—
86,118	38·44	0·1030	129,074	2·06	0·66	9·62	1
82,344	36·76	0·1603	116,036	1·90	0·71	13·42	2
73,080	32·62	—	—	2·07	—	14·74	—
72,737	32·47	0·1191	115,967	1·96	0·62	17·95	1

[4] The bars have broken outside the 5-feet division. Comp. pp. 39 and 40.
[5] (In the original tables this is expressed in *pounds* only. It was, however, thought desirable in these tables to give, in addition, the breaking weight per sq. inch on original mean area in *tons.—Translator.*)

TABLE I. (*continued*).—RESULTS of EXPERIMENTS on the TENSILE STRENGTH at a temperature

Observer.	No. of experiment.	Description of steel or iron.	Section as to Form.	Section as to Mean area.	Load applied per sq. in. of mean area.	Weight laid on per sq. in. at the limit of elasticity after Wertheim's definition.	Weight per sq. in. at the maximum curvature.[1]
—	—	—	—	sq. in.	lbs.	lbs.	lbs.
Thalén	31[4]	N. P. 3	Square.	0·2362	7,067	33,555	34,310
Cronstrand ..	32	,,	Round.	0·1952	—	—	37,741
Thalén	33[4]	N. 3	Square.	0·2392	10,841	25,320	36,368
,, ...	34[4]	,,	Round.	0·1903	13,380	36,780	38,427
,, ...	35	,,	,,	0·1879	17,086	36,368	37,054
,, ...	36[4]	B. 3	Square.	0·2351	11,047	30,810	37,741
,, ...	37[4]	,,	Round.	0·1937	9,949	24,360	37,054
Cronstrand ..	38	,,	,,	0·1906	—	—	39,113
,, ..	39	P. 3	,,	0·1899	10,155	23,879	33,623
,, ..	40	,,	,,	0·1956	—	—	34,996
Thalén	41[4]	G. 3	Square.	0·2328	11,116	31,084	41,172
,, ...	42[4]	,,	,,	0·2344	—	—	40,485
Cronstrand ..	43	,,	Round.	0·1937	—	—	41,858
Thalén	44	N. H-iron	Square.	0·2336	11,116	26,006	29,506
,, ...	45	,,	Round.	0·1928	13,449	26,967	30,192
Cronstrand ..	46	,,	,,	0·1952	—	—	28,820
Thalén	47	N. P-iron	,,	0·1921	—	—	28,820
,, ...	48	,,	,,	0·1930	13,449	22,095	30,879
,, ...	49	N-iron	Square.	0·2362	11,047	26,761	29,506
,, ...	50	,,	Round.	0·1906	9,675	31,565	33,623
Cronstrand ..	51	,,	,,	0·1915	—	—	34,310
Thalén	52	B-iron	Square.	0·2386	10,979	27,722	30,879
,, ...	53	,,	Round.	0·1899	9,675	21,889	33,623
,, ...	54	P-iron	Square.	0·2378	10,910	27,516	28,134
,, ...	55	,,	,,	0·2367	—	—	29,506
,, ...	56	,,	Round.	0·1913	—	—	30,879
,, ...	57	,,	,,	0·1918	11,087	27,036	30,879
,, ...	58	G-iron	Square.	0·2339	5,146	26,967	30,879
,, ...	59	,,	,,	0·1915	11,087	31,908	32,937

[1] What is meant by maximum curvature is explained p. 17. Comp. pp. 27, 28, and 33.
[2] The elongation on the foot-division at which the fracture occurred is not reckoned. Comp. note on p. 16.
[3] Comp. p. 10.

of Puddled Steel and Puddled Iron from Surahammar (Sweden) of about 60° Fahr.

Breaking weight per sq. in. on original mean area.		Section at fracture.	Breaking weight per sq. in. on section of fracture.	Ratio between the loads at fracture and at maximum curvature.	Ratio between the area of fracture and original area.	Elongation after rupture.[3]	Number of clamps used in the experiment.[3]
lbs.	tons.[5]	sq. in.	lbs.	—	—	per cent.	—
66,767	29·80	0·1358	116,036	1·94	0.57	10·63	—
68,894	30·75	0·1087	123,721	1·82	0·55	17·82	1
68,208	30·31	0·1384	117,889	1·88	0·57	12·11	—
71,639	31·98	0·1087	125,437	1·86	0·57	11·31	—
72,531	32·38	0·1156	117,889	1·96	0·61	14·40	—
80,079	35·74	0·1675	112,399	2·12	0·71	7·93	—
72,256	32·25	0·1101	110,752	2·13	0·65	6·42	—
79,324	35·41	0·1030	116,242	2·03	0·61	10·22	—
62,993	28·12	0·1135	106,566	1·87	0·59	18·23	1
61,140	27·29	0·1227	97,440	1·75	0·62	14·57	—
86,461	38·59	0·1752	114,869	2·10	0·75	6·03	—
73,766	32·93	—	—	1·82	—	5·97	—
86,667	38·69	0·1453	115,555	2·07	0·75	11·34	2
47,622	21·27	0·1060	104,988	1·61	0·45	22·04	—
49,543	22·11	0·0862	110,684	1·64	0·44	22·85	—
48,926	21·84	0·0862	110,684	1·70	0·44	17·29	—
46,318	20·67	0·0862	103,135	1·61	0·46	18·15	—
45,632	20·37	0·0832	105,674	1·48	0·43	21·82	—
52,219	23·31	0·0985	125,094	1·77	0·41	21·36	—
52,013	23·22	0·0862	115,007	1.55	0·45	18·20	—
53,729	23·98	0·0955	107,664	1·56	0·50	19·09	—
48,926	21·84	0·0985	118,506	1·58	0·41	21·87	—
50,229	22·42	0·0832	114,595	1·49	0·43	21·30	—
46,798	20·89	0·0913	121,731	1·66	0·38	19·85	—
45,838	20·40	0·0892	121,526	1·55	0·37	16·45	—
49,886	22·26	—	—	1·62	—	20·69	—
43,710	19·51	0·0463	122,898	1·55	0·39	22·50	—
50,298	22·45	0·0949	124,064	1·63	0·40	17·34	—
51,739	23·09	0·0862	114,938	1·57	0·45	19·12	—

[4] The bars have broken outside the 5-feet division. Comp. pp. 39 and 40.
[5] (In the original tables this is expressed in *pounds* only. It was, however, thought desirable in these tables to give, in addition, the breaking weight per square inch on original mean area in *tons*.—*Translator*.)

Table II.—Average Results obtained by rupture of 130 bars of Puddled Steel 94 were tested by Thalén, 21 by Ångström, and 15 by Cronstrand.

Description of Steel or Iron.	SQUARE BARS. No. of bars experimented upon.	Elongation by rupture.*	Breaking weight per square inch on the original mean area.		Breaking weight per square inch on the section of fracture.
		per cent.	lbs.	tons.	lbs.
Hard puddled steel, marked N H 1	3	10·01	85,020	37·95	118,026
,, ,, N P 1	3	3·91	105,331	47·02	140,671
,, ,, N 1	3	7·76	84,647	37·78	104,919
,, ,, B 1	3	3·25	87,559	39·08	131,681
,, ,, P 1	3	6·13	87,216	38·93	127,152
,, ,, G 1	3	6·13	85,363	38·10	111,233
Average ..	..	6·20	89,189	39·81	122,240
Middling hard puddled steel, marked N H 2	3	6·27	77,677	34·67	121,251
,, ,, N P 2	3	5·55	86,118	38·44	118,095
,, ,, N 2	3	7·58	77,952	34·80	107,321
,, ,, B 2	3	5·48	84,402	37·67	116,654
,, ,, P 2	3	7·40	74,384	33·20	112,948
,, ,, G 2	3	9·59	83,236	37·15	117,751
Average ..	..	6·98	80,628	35·99	115,670
Soft puddled steel, marked N H 3	2	10·40	72,188	32·22	110,684
,, ,, N P 3	2	11·59	66,081	29·50	113,634
,, ,, N 3	3	11·44	69,923	31·21	113,497
,, ,, B 3	2	7·18	79,867	35·65	112,536
,, ,, P 3	2	14·76	61,689	27·54	110,340
,, ,, G 3	3	7·24	77,883	34·76	114,869
Average ..	..	10·43	70,272	31·81	112,593
Puddled iron, marked N H	2	22·42	47,279	21·01	110,066
,, ,, N P	3	21·76	45,014	20·09	113,634
,, ,, N	2	21·10	51,876	23·15	126,947
,, ,, B	2	21·10	47,896	21·38	124,476
,, ,, P	3	18·90	47,416	21·16	123,035
,, ,, G	2	16·87	50,435	22·51	126,466
Average ..	..	20·36	48,319	21·55	120,770

* The elongation on that foot division at which fracture took place is not taken into account. Compare Note, page 16.

and Iron from Surahammar (Sweden), including those in Table I. Of these bars All experiments made at a temperature of about 60° Fahrenheit.

Description of Steel or Iron.	ROUND BARS. No. of bars experimented upon.	Elongation by rupture.*	Breaking weight per square inch on the original mean area.		Breaking weight per square inch on the section of fracture.
		per cent.	lbs.	tons.	lbs.
Hard puddled steel, marked N H 1	3	4·98	84,647	37·78	120,290
,, ,, N P 1	3	4·58	104,714	46·74	142,660
,, ,, N 1	2	6·61	78,158	34·89	112,399
,, ,, B 1	3	4·41	88,451	39·48	114,115
,, ,, P 1	3	9·47	73,629	32·87	122,143
,, ,, G 1	4	6·32	81,795	36·51	125,437
Average ..	..	6·06	85,232	38·04	122,840
Middling hard puddled steel, marked N H 2	3	6·95	83,922	37·47	116,928
,, ,, N P 2	2	5·57	93,803	41·87	132,093
,, ,, N 2	3	8·92	77,471	34·58	112,948
,, ,, B 2	3	5·36	82,618	36·88	114,526
,, ,, P 2	4	6·23	79,530	35·50	115,967
,, ,, G 2	2	7·69	77,883	34·76	104,302
Average ..	..	6·79	82,571	36·84	116,127
Soft puddled steel, marked N H 3	2	15·32	73,080	32·62	106,841
,, ,, N P 3 . ..	2	14·56	67,384	30·08	121,526
,, ,, N 3	3	12·74	72,256	32·25	121,663
,, ,, B 3	3	6·86	74,246	33·14	113,497
,, ,, P 3	3	15·57	62,512	27·90	96,205
,, ,, G 3	2	9·50	86,323	38·53	115,487
Average ..	..	12·43	72,633	32·42	112,536
Puddled iron, marked N H	3	19·75	48,926	21·84	106,429
,, ,, N P	2	19·98	45,975	20·52	104,371
,, ,, N	3	19·25	53,249	23·77	114,595
,, ,, B	3	17·73	48,651	21·71	127,152
,, ,, P	3	19·87	49,475	22·08	124,059
,, ,, G	2	19·48	49,100	21·91	111,507
Average ..	..	19·34	49,229	21·97	114,352

* The elongation on that foot division at which fracture took place is not taken into account. Compare Note page 16.

TABLE III.—RESULTS of EXPERIMENTS on TENSILE STRENGTH, made with Bessemer

No. of the experiment.	Description of Iron or Steel.	Amount of carbon. According to determination made by the manufacturer.	Amount of carbon. According to determination made at the School of Mines, Fahlun.	Amount of phosphorus according to experiments made at the School of Mines, Fahlun.	Sectional area. Form.	Sectional area. Mean Area.
		per cent.	per cent.	per cent.	—	sq. in.
1	Tilted Bessemer steel from Högbo ..	1·2	—	—	Round.	0·1918
2	,, ,, ..	1·2	1·35	—	,,	0·1969
3	,, ,, ..	1·0	1·14	0·018	,,	0·1754
4	,, ,, ..	1·0	—	—	,,	0·1829
5	,, ,, ..	0·9	—	—	,,	0·1872
6	,, ,, ..	0·9	1·05	—	,,	0·1829
7	,, ,, ..	0·6	0·68	—	,,	0·1882
8	,, ,, ..	0·6	—	—	,,	0·1855
9	Tilted Bessemer iron from Högbo ..	0·3	0·33	—	,,	0·1754
10	,, ,, ..	0·3	—	—	,,	0·1891
11[1]	,, ,, ..	0·3	—	—	,,	0·1846
12	Rolled Bessemer steel from Carlsdal of the older number of hardness 3	—	1·85	—	Square.	0·2441
13	,, ,, ..	—	—	—	,,	0·2441
14	,, ,, ..	—	2·16	—	Round.	0·2009
15	,, ,, ..	—	—	—	,,	0·2045
16	,, ,, ..	—	0·99	—	Square.	0·2593
17	,, ,, ..	—	0·98	—	,,	0·2593
18	,, ,, ..	—	1·39	—	Round.	0·1868
19	,, ,, ..	—	1·19	—	,,	0·1909
20	.. ..	0·40	0·42	—	Square.	0·2313
21	.. ..	0·40	—	—	,,	0·2283
22	.. ..	0·32	—	—	,,	0·2321
23	.. ..	0·32	0·38	0·023	,,	0·2313
24	.. ..	0·32	—	—	,,	0·2294
25	Rolled cast steel (Uchatius steel) from Wikmanshyttan, of hardness No. 0,2	—	1·57	—	Round.	0·1876
26	,, ,, ,, ,,	—	1·56	—	,,	0·1799
27	,, ,, ,, No. 1	—	—	—	,,	0·1775
28	,, ,, ,, ,,	—	1·16	0·011	,,	0·1749
29	,, ,, ,, ,,	—	1·22	—	,,	0·1691
30	,, ,, ,, No. 3	—	0·69	—	,,	0·1913
31	,, ,, ,, ,,	—	—	—	,,	0·1702
32	Tilted cast steel from F. Krupp, marked with 1 crown	—	0·62	0·022	,,	0·2121
33	,, ,, ,, 2 crowns	—	0·61	0·03	,,	0·2094

[1] The bar annealed before the experiment.

Steel and Iron, and with Cast Steel at a Temperature of about 60° Fahr.

Load per sq. in. at the limit of elasticity.	Breaking weight per sq. in. on the original mean area.		Area of fracture.	Breaking weight per sq. inch on the area of fracture.	Ratio between the load at fracture and at the limit of elasticity.	Ratio between the sectional area of fracture and that of the bar originally.	Elongation by rupture.	Mean elongation between the limits of elasticity and fracture for an increase in the load of 100 lbs. per sq line = 6862 lbs. per sq. in.
lbs.	lbs.	tons.	sq. in.	lbs.	—	—	per cent.	per cent.
78,913	105,125	46·93	0·1754	113,017	1·33	0·93	2·1	0·55
76,511	107,184	47·85	0·1537	137,308	1·40	0·77	2·8	0·65
85,431	127,564	56·94	0·1053	216,153	1·49	0·59	2·9	0·47
78,913	125,574	56·06	0·1088	211,075	1·59	0·59	2·8	0·41
67,147	97,783	43·65	0·0955	191,518	1·45	0·51	3·9	0·87
68,620	108,213	48·30	0·1122	176,422	1·57	0·61	2·9	0·50
68,620	101,214	45·18	0·1227	155,218	1·47	0·65	3·7	0·78
69,649	106,704	47·63	0·1170	169,079	1·53	0·63	4·6	0·85
52,151	71,364	31·85	0·0663	191,930	1·37	0·37	5·5	1·95
56,268	71,296	31·82	0·0717	188,012	1·27	0·38	6·5	2·96
37,054	67,933	30·32	0·0585	214,368	1·83	0·37	10·0	2·22
57,640	99,842	44·61	0·2385	102,173	1·73	0·97	1·75	0·28
61,758	89,549	39·97	0·2441	89,549	1·45	1·00	1·15	0·28
64,502	86,804	38·75	0·1945	89,617	1·34	0·97	2·96	0·91
—	97,783	43·65	0·1946	102,724	—	0·95	3·9	—
65,875	102,998	45·98	0·2514	106,223	1·56	0·97	3·7	0·68
—	111,987	49·99	0·2441	118,918	—	0·94	3·9	—
69,992	135,936	60·68	0·1058	191,175	1·94	0·71	5·5	0·57
67,933	139,916	62·46	0·1580	168,942	2·06	0·82	4·1	0·39
—	68,757	30·69	0·0985	161,325	—	0·43	16·7	—
34,310	70,472	31·46	0·1189	136,759	2·05	0·51	15·2	2·88
37,741	66,081	29·50	0·0914	167,844	1·76	0·39	15·7	3·80
34,990	64,708	28·88	0·1060	141,219	1·85	0·46	16·7	3·85
34,653	65,257	29·13	0·0878	170,383	1·88	0·38	17·7	3·97
—	116,516	52·01	0·1631	133,946	—	0·87	1·9	—
83,167	121,388	54·19	0·1771	123,378	1·46	0·98	2·5	0·45
72,737	138,886	62·00	0·1453	169,628	1·91	0·81	4·5	0·46
71,707	139,847	62·43	0·1533	159,610	1·95	0·88	4·6	0·46
73,080	144,719	64·60	0·1610	151,993	1·98	0·95	4·5	0·43
67,147	103,547	46·22	0·1191	166,334	1·54	0·62	11·3	2·14
60,728	118,643	52·96	0·1226	164,688	1·95	0·72	10·8	1·28
50,092	85,431	38·13	0·0972	186,440	1·70	0·46	6·4	1·24
55,925	82,549	36·85	0·0991	172,304	1·47	0·48	5·5	1·41

TABLE IV.—RESULTS of EXPERIMENTS on TENSILE STRENGTH,

No. of experiment.	Description of Iron.	Amount of carbon determined at the school of mines, Fahlun.	Amount of phosphorus determined at the school of mines, Fahlun.	Sectional area.	
				Form.	Mean Area.
		per cent.	per cent.	—	sq. in.
1	Rolled puddled iron from Low Moor	—	—	Round.	0·206
2	,, ,, ...	0·21	0·068	,,	0·204
3	,, ,, ...	—	—	,,	0·206
4	,, ,, ...	—	—	,,	0·2007
5	,, ,, ...	—	—	,,	0·196
6	from Middlesbro'-on-Tees, marked "Cleveland"	—	—	,,	0·313
7	,, ,, ,,	—	—	,,	0·308
8	,, ,, ,,	—	—	,,	0·309
9	,, ,, ,,	—	0·24	,,	0·311
10	,, ,, ,,	0·07	0·295	,,	0·309
11	,, ,, ,,	—	—	,,	0·304
12	,, ,, ,,	—	0·27	,,	0·306
13	,, from Dudley	—	—	,,	0·192
14	,, ,, ...	0·09	0·346	,,	0·2003
15	,, ,, ...	0·09	0·346	,,	0·196
16	,, ,, ...	—	—	,,	0·187
17	,, ,, ...	—	—	,,	0·189
18	Planed and rolled Sample— from the outside of an engine tyre from Low Moor	—	0·158	Square.	0·270
19	,, ,, ,,	—	—	,,	0·270
20	,, ,, ,,	—	—	,,	0·268
21	from the head of a rail from Cwm Avon (Wales)	—	—	,,	0·262
22	,, ,, ,,	—	0·240	,,	0·262
23	,, ,, ,,	—	—	,,	0·262
24	from the stem of a rail from Cwm Avon (Wales)	—	0·222	,,	0·272
25	,, ,, ,,	—	—	,,	0·270
26	Rolled puddled iron from Motala Works (Sweden)..	0·2	0·02	Round.	0·188
27	,, ,, ,,	—	—	,,	0·193
28	,, ,, ,,	—	—	,,	0·191
29	,, ,, ,,	—	—	,,	0·183
30	,, ,, ,,	—	—	,,	0·188
31	,, ,, ,,	—	—	,,	0·192
32	Rolled iron made in a charcoal hearth— from Åryd Småland (Sweden)	0·07	—	Square.	0·277
33	,, ,, ,,	0·18	0·264	,,	0·282
34	,, ,, ,,	—	—	,,	0·278
35	,, ,, ,,	0·07	—	,,	0·275
36	,, ,, ,,	—	—	,,	0·278
37	from Hallstahammar, Westmanland (Sweden)	0·07	—	,,	0.215
38	,, ,, ,,	—	—	,,	0·213
39	,, ,, ,,	—	—	,,	0·215
40	Rolled iron made in a Lancashire hearth— from Lesjöforss, Wermland (Sweden)	0·07	0·022	,,	0·243
41	,, ,, ,,	—	—	,,	0·230

REMARKS.—No. 11 had been slightly annealed before the experiments.

No. 12 had previously been strongly annealed. One part of the broken bar was heated by repeated annealing to such an extent that it was much bent: it was afterwards filed square for a length of 4 inches, was divided into inches, and examined. It now broke by a weight of 59,630 lbs. per sq. in., after an elongation of 18°/₀, the inch where the fracture took place not being included. The fracture was semi-crystalline and semi-fibrous.

Nos. 14 and 15 had originally been one bar.

No. 16 had been strongly annealed.

made with Iron at a Temperature of about 60° Fahrenheit.

Load per sq. in. at the limit of elasticity.	Breaking weight per sq. in. of the original mean area.		Area of fracture.	Breaking weight per sq. in. of the area of fracture.	Ratio between the load at fracture and at the limit of elasticity.	Ratio between the sectional area of the fracture and that of the bar originally.	Elongation by rupture.	Mean elongation between the limit of elasticity and fracture for an increase in the load of 6862 lbs. per sq. in.
lbs.	lbs.	tons.	sq. in.	lbs.	—	—	per cent.	per cent.
35,682	55,650	24·84	0·095	120,496	1·56	0·46	20·1	6·91
36,025	58,944	26·31	0·092	130,583	1·63	0·45	20·5	6·13
35,682	52,974	23·64	0·102	107,253	1·48	0·49	20·6	8·17
—	52,700	23·54	0·095	110,822	—	0·47	19·0	—
—	56,746	25·33	0·095	116,654	—	0·49	18·0	—
32,937	58,464	26·10	0·1699	106,978	1·77	0·54	16·3	4·11
—	61,414	27·50	0·174	109,174	—	0·56	18·9	—
31,222	53,317	23·80	0·187	88,176	1·71	0·60	18·8	5·84
33,623	56,474	25·21	0·1698	103,478	1·68	0·54	19·6	5·88
—	72,531	32·38	0·205	109,723	—	0·66	18·7	—
31,565	61,071	27·26	0·189	108,076	1·93	0·62	14·6	3·39
33,280	57,023	25·45	0·178	98,057	1·70	0·54	14·1	4·18
35,339	55,856	24·93	0·151	71,296	1·58	0·78	12·6	4·21
28,134	41,738	18·63	0·165	57,778	1·50	0·82	6·6	2·95
28,683	47,553	21·22	0.151	62,032	1·66	0·76	7·4	2·69
30,879	51,808	23·12	0·1702	57,023	1·67	0·90	7·8	2·57
34,653	52,013	23·22	0·141	69,649	1·50	0·75	8·3	3·29
34,996	53,592	23·92	0·156	92,568	1·53	0·58	12·9	4·76
—	52,906	23·66	0·2109	67,727	—	0·78	10·2	—
—	53,798	24·01	0·165	87,353	—	0·62	13·2	—
30,879	44,465	19·85	0·238	48,994	1·44	0·91	4·7	2·37
—	48,720	21·75	0·250	51,190	—	0·95	6·6	—
—	50,847	22·69	0·214	62,169	—	0·82	8·5	—
—	44,259	19·75	0·264	45,632	—	0·97	3·4	—
—	43,642	19·48	0·250	47,485	—	0·92	3·2	—
29,506	52,631	23·49	0·098	100,665	1·74	0·52	17·3	5·29
26,761	45,632	20·37	0·137	64,091	1·74	0·71	11·4	4·14
26,761	46,181	20·61	0·112	78,775	1·73	0·59	11·2	3·96
32,937	50,710	22·63	0·083	111,507	1·54	0·45	13·4	5·17
25,389	48,651	21·71	0·058	157,551	1·92	0·31	13·3	3·92
27,104	46,867	20·92	0·112	80,148	1·73	0·58	17·8	6·18
37,397	65,669	29·31	0·141	129,417	1·61	0·51	14·1	3·42
40,485	63,473	28·33	0·232	76,864	1·57	0·82	8·2	2·44
42,545	61,758	27·57	0·261	65,737	1·42	0·94	6·5	2·32
47,004	60,728	27·22	0·275	60,728	1·29	1·00	5·5	2·75
38,084	47,690	21·29	0·267	49,612	1·24	0·96	1·1	0·78
27,104	50,916	22·73	0·094	115,761	1·87	0·44	16·7	4·85
27,448	50,572	22·57	0·059	182,735	1·84	0·27	18·6	5·51
27,791	50,916	22·73	0·076	142,866	1·83	0·35	19·9	5·90
24,360	45,014	20·09	0·056	192,753	1·85	0·23	22·0	7·31
30,879	48,720	21·75	0·084	132,985	1·58	0·37	20·3	7·81

Nos. 27 and 28 had originally been one bar.

No. 32 broke at first three times outside the marks, near the thread, but tried with clamps it broke in the middle by a weight of 65,679 lbs. per sq. in., with an elongation of 14°/₀.

No. 35 had previously been slightly annealed.

No. 36 had previously been strongly annealed: broke just outside the mark, but tested again it broke by a weight of 49,337 lbs, per sq. in., with an elongation of 1·5°/₀.

TABLE V.—Shewing the increase of the PERMANENT ELONGATIONS by gradually-increased Loads.

1. Cast steel from Wikmanshyttan. No. 30. Table III. Stretching weight = 16,880 lbs. per sq. in.			2. Puddled steel from Surahammar. N. P. 1. No. 3. Table I. Stretching weight = 12,224 lbs. per sq. in.			3. Puddled steel from Surahammar, B 3, stretched in water. Section, round. Mean area = 0·2367 sq. in. Stretching weight = 12·077 lbs. per sq. in.			4. Puddled iron from Middlesbro'-on-Tees. No. 9. Table IV. Stretching weight = 9188 lbs. per sq. in.			5. Puddled iron from Motala. No. 27. Table IV. Stretching weight = 14,753 lbs. per sq. in.		
Loads per sq. in.	Permanent elongation.	Increase of length at each stretching.	Loads per sq. in.	Permanent elongation.	Increase of length at each stretching.	Loads per sq. in.	Permanent elongation.	Increase of length at each stretching.	Loads per sq. in.	Permanent elongation.	Increase of length at each stretching.	Loads per sq. in.	Permanent elongation.	Increase of length at each stretching.
lbs.	per cent.	per cent.	lbs.	per cent.	per cent.	lbs.	per cent.	per cent.	lbs.	per cent.	per cent.	lbs.	per cent.	per cent.
38941·85	0·000	—	31290·72	0·000	—	27821·29	0·000	—	15178·744	0·0000	—	16243·04	0·0005	0·0005
44452·036	0·000	—	—	—	—	28607·678	0·000	—	—	—	—	17690·236	0·0011	0·0006
49962·222	0·002	0·002	35270·68	0·001	0·001	29396·808	0·001	0·001	24758·096	0·0000	—	19138·118	0·0020	0·0009
55472·408	0·004	0·002	37260·66	0·001	0·000	30179·076	0·004	0·003	25952·084	0·0004	0·0004	21059·478	0·006	0·004
58224·070	0·005	0·001	39319·26	0·001	0·000	30968·206	0·009	0·005	27152·934	0·0014	0·0010	22987·7	0·008	0·002
60975·732	0·008	0·003	41309·24	0·003	0·002	31757·336	0·011	0·002	27448·	0·0018	0·0004	24915·922	0·021	0·013
62080·514	0·010	0·002	43299·22	0·004	0·001	32546·466	0·014	0·003	27749·928	0·0023	0·0005	26363·804	0·048	0·017
63178·434	0·012	0·002	45289·20	0·006	0·002	33328·734	0·018	0·004	28044·994	0·0030	0·0007	27331·346	0·103	0·055
64283·216	0·015	0·003	47279·18	0·007	0·001	34117·864	0·023	0·005	28346·922	0·0031	0·0001	28292·026	0·286	0·183
65387·998	0·018	0·003	49337·78	0·011	0·004	34906·994	0·031	0·008	28648·85	0·0033	0·0002	29259·568	0·576	0·290
66485·918	0·021	0·003	51327·76	0·017	0·006	35689·262	0·053	0·022	28943·916	0·0042	0·0009	30220·248	1·036	0·460
67590·70	0·025	0·004	53317·74	0·024	0·007	36478·392	0·098	0·045	29245·844	0·0045	0·0003	31187·79	1·764	0·728
68688·62	0·030	0·005	55307·72	0·035	0·011	37260·66	0·196	0·098	29545·772	0·0052	0·0007	32148·47	2·042	0·278
69793·402	0·036	0·006	57297·70	0·063	0·028	38056·652	0·345	0·149	29842·838	0·0057	0·0005	34076·692	2·622	0·580
70891·322	0·042	0·006	59356·30	0·114	0·051	38838·92	0·421	0·076	30144·766	0·0058	0·0001	36004·914	3·283	0·661
71996·104	0·050	0·008	63679·36	0·249	0·135	39628·05	0·515	0·094	30446·694	0·0063	0·0005	37933·136	4·098	0·815

73094·024	0·062	0·012	67247·60	0·424	0·175	41199·448	0·664	0·149	30755·484	0·0071	0·0008	39861·358	5·188	1·090
74198·806	0·079	0·017	,,	0·454	0·030	42777·708	0·767	0·103	31043·688	0·008	0·0009	41789·58	6·567	1·379
75296·726	0·098	0·019	,,	0·469	0·015	44349·106	0·917	0·150	31338·754	0·009	0·001	43717·802	8·747	2·180
76401·508	0·129	0·031	,,	0·479	0·010	45927·366	1·040	0·123	31640·682	0·010	0·001	45646·024	11·617	2·870
77506·290	0·199	0·070	,,	0·486	0·007	47498·764	1·192	0·152	31942·610	0·011	0·001	Broke.		
78604·210	0·284	0·085	,,	0·493	0·007	49070·162	1·35	0·16	32237·676	0·012	0·001			
79708·992	0·363	0·079	,,	0·497	0·004	50648·422	1·51	0·16	32539·604	0·014	0·002			
80806·912	0·406	0·043	,,	0·503	0·006	52226·682	1·67	0·16	32841·532	0·016	0·002			
81911·694	0·428	0·022	,,	0·506	0·003	53798·08	1·89	0·22	33136·598	0·020	0·004			
82989·028	0·453	0·025	,,	0·509	0·003	55369·478	2·13	0·24	33438·526	0·028	0·008			
84114·396	0·485	0·032	71364·80	0·611	0·102	56940·876	2·37	0·24	33733·592	0·036	0·008			
85219·178	0·515	0·030	75344·76	0·821	0·210	58519·136	2·67	0·30	34035·52	0·051	0·015			
87415·018	0·569	0·054	79324·72	1·061	0·240	60090·534	2·89	0·22	34337·448	0·078	0·027			
89624·582	0·634	0·065	83373·30	1·297	0·236	61668·794	3·31	0·42	34632·514	0·125	0·047			
91827·284	0·702	0·068	87421·88	1·615	0·318	63240·192	3·83	0·52	34934·442	0·180	0·055			
94029·986	0·777	0·075	89000·14	1·753	0·138	64880·21	4·35	0·52	35236·370	0·280	0·100			
96232·688	0·864	0·087	90578·40	1·904	0·151	66389·85	5·11	0·76	35531·436	0·401	0·121			
98435·390	0·954	0·090	92225·28	2·125	0·221	67961·248	6·01	0·90	—	—	—			
100638·092	1·048	0·094	93803·54	2·318	0·193	69539·508	7·17	1·16	36135·292	0·925	—			
102840·794	1·141	0·093	95381·80	2·539	0·221	70417·844	8·89	1·72	36430·358	1·082	0·157			
107246·198	1·32	0·179	97028·68	2·789	0·248	71900·036	9·96	1·07	39127·124	2·05	0·968			
111651·602	1·54	0·22	98538·32	3·007	0.220	Broke.			—	—	—			
116063·868	1·76	0·22	Broke.						42118·956	3·07	—			
120469·272	2·02	0·25							—	—	—			
124874·676	2·34	0·32							45110·788	4·37	—			
125979·448	2·8	0·46							—	—	—			
—	—	—							48109·482	5·04	—			
144705·856	4·52								—	—	—			
Broke.									50497·458	7·06	—			
									—	—	—			
									52889·158	10·2	—			
									—	—	—			
									55293·996	15·2	—			
									56487·984	19·6	4·4			
									Broke.					

Table VI.—Results of Experiments made at about 60° Fahrenheit, in order to
All the Bars tested were filed square in the

Those with brackets preceding the numbers

No. of experiment.	Description of Iron or Steel.	Treatment of the bar before the experiment.
	Bessemer Steel from Högbo—	
1	Marked 0·9 of the bar No. 5 in Table III.	Heated to redness and hardened in water .. .. ..
2	,, ,, ,, ...	,, ,, ,, in oil .. .. ..
3	,, ,, ,, ...	,, ,, ,, ,, ...
4	,, 0·6 ,, No. 7 ,, ...	,, ,, , hardened in water, and heated for half an hour at 482° Fahr. .. ..
5	,, ,, ,, ...	
	Bessemer Iron from Högbo—	
6	Marked 0·3	Heated to redness and hardened in water .. .. ..
7	,, ...	,, ,, slowly cooled in warm coal dust
	Bessemer Steel from Carlsdal—	
8	Marked 0·4 of the bar No. 20 in Table III.	,, ,, hardened in oil .. ..
9	,, ,, ,, ...	,, ,, slowly cooled in warm coal dust
10	,, ,, ,, ...	,, ,, hardened in water .. .. ..
	Uchatius Steel from Wikmansbyttan—	
11	No. 0·2 of the bar No. 26 in Table III.	,, ,, ,, in oil .. .. ..
12	No. 1	,, ,, ,, ,, ...
13	,, ...	Not heated but examined in its original state .. ..
14	,, ...	Heated to redness and cooled slowly in warm coal dust .. ..
15	,, ...	
16	,, ...	Strongly heated and hardened in oil .. ..
17	No. 1 of the bar No. 28 in Table III.	Slightly heated and hardened in water .. .. ..
18	,, ,, ,, ...	Slightly heated, hardened in water, and warmed half an hour in a bath of paraffine at 284° .. ..
19	,, ,, ,, ...	Strongly heated and hardened in oil .. .. ..
20	No. 3	Heated to redness, hardened in water, and heated half an hour in paraffine at 302° .. .. ..
21	,, ...	
22	,, ...	Heated to redness and hardened in oil .. .. ..
23	,, ...	,, ,, ,, ,, ...
24	,, ...	,, ,, slowly cooled in warm coal dust
25	No. 3 of the bar No. 30 in Table III.	,, ,, hardened in water, and heated half an hour at 482° .. ..
26	,, ,, ,, ...	Heated to redness and hardened in oil .. .. ..
	Cast-steel from Krupp—	
27	Marked with one crown	,, ,, hardened in water, and heated half an hour at 464° .. ..
28	,, ,, ...	Heated to redness and hardened in oil .. .. ..
29	,, ,, ...	,, ,, ,, ,, ...
	Puddled Iron from Surahammar—	
30	Marked B.	,, ,, ,, in water .. .. ..
31	,, ...	,, ,, ,, ,, ...
32	,, ...	,, ,, slowly cooled in hot coal dust
	Iron made in a charcoal hearth from Åryd—	
33	Of the bar No. 34 in Table IV.	,, ,, hardened in water .. .. ..
34	,, ,, ,, ...	,, ,, ,, ,, ...
35	,, No. 35 ,, ...	,, ,, ,, ,, ...
	Iron made in charcoal hearth from Hallsthammar—	
36	Of the bar No. 37 in Table IV	,, ,, ,, ,, ...
37	,, ,, ,, ...	,, ,, slowly cooled in hot coal dust
38	Iron made in charcoal hearth from Lesjöforss	,, ,, hardened in water .. .. ..
39	,, ,, ,, ...	,, ,, ,, ,, ...
40	,, ,, ,, ...	,, ,, slowly cooled in hot coal dust
41	,, ,, ,, ...	,, ,, hardened in water .. .. ..
42	,, ,, ,, ...	,, ,, slowly cooled in hot coal dust

* Several other Steel bars, containing One per cent. and more of Carbon, were examined after having been exposed have not been mentioned in these Tables.

ascertain the effect of Hardening on the Extensibility and Strength of Iron and Steel.
middle, for a length of from 0·58 to 4·65 inches.

were originally parts of the same bar.

Amount of carbon.		The filed and divided part as to		Breaking weight per square inch of the original mean area of the filed part of the bar.		Area of fracture.	Ratio between the area of fracture and the original mean area.	Elongation by rupture, the place of fracture not taken into account.
In the bar tried.	In other bars of the same kind.	Length.	Mean area.					
per cent.	per cent.	inches.	square inch.	lbs.	tons.	square inch.		per cent.
—	1·05	2·32	0·069	less than 41,172	less than 18·38	0·069	1·00	0·0
—	1·05	2·32	0·068	173,951	77·65	0·068	1.00	0·0
—	1·05	1·74	0·070	115,350	51·49	0·070	1·00	0·0
0·68	—	3·48	0·086	104,919	46·83	0·086	0·99	1·7
0·68	—	3·48	0·089	101,283	45·21	0·054	0·60	1·5
—	0·33	2·32	0·076	79,873	35·65	0·032	0·42	13·0
—	0·33	2·32	0·077	51,259	22·88	0·021	0·27	19·0
0·42	—	1·04	0·100	102,243	45·64	0·050	0·50	—
0·42	—	1·04	0·099	77,060	34·40	0·046	0·46	—
0·42	—	1·04	0·079	100,253	44·75	0·079	1·00	—
1·56	—	2·32	0·065	132,916	59·33	0·094	0·90	1·3
1·22	—	0·93	0·080	195,018	87·06	0·094	0·74	1·1
1·22	—	0·81	0·079	152,336	68·00	0·071	0·89	—
1·22	—	1·04	0·097	93,185	41·60	0·054	0·55	—
1·22	—	0·93	0·091	84,814	37·86	0·045	0·50	—
1·22	—	1·16	0·100	101,351	45·24	0·100	1·00	0·0
1·16	—	1·16	0·080	143,209	63·93	0·070	0·87	—
1·16	—	3·48	0·092	131,613	58·75	0·071	0·77	6·0
1·16	—	1·74	0·068	less than 54,896	less than 24·50	0·068	1·00	0·0
0·78	—	1·61	0·085	83,441	37·25	0·084	0·99	0·0
0·78	—	1·74	0·083	89,892	40·13	0·083	1·00	0·0
0·78	—	1·16	0·095	146,915	65·58	0·095	1·00	—
0·78	—	0·93	0·083	168,530	75·23	0·076	0·91	—
0·78	—	0·93	0·091	96,891	43·25	0·094	0·64	—
0·69	—	3·48	0·088	108,899	48·61	0·048	0·55	3·0
0·69	—	1·74	0·067	136,691	61·02	0·067	1·50	2·0
—	0·62	3·48	0·111	122,280	54·58	0·105	0·93	0·0
—	0·62	0·58	0·100	171,687	76.64	0·100	1·00	—
—	0·62	0·58	0·103	135,836	60·64	0·098	0·95	—
—	0·20	2·67	0·151	69,306	30·94	0·081	0·53	6·2
—	0·20	1·51	0·143	68,757	30·69	0·113	0·79	—
—	0·20	1·62	0·148	46,730	20·86	0·054	0·36	—
—	0·07	3·48	0·158	66,767	29·80	0·043	0·53	25·0
—	0·07	1·04	0·157	60,660	27·08	0·125	0·79	—
0·07	—	3·48	0·132	73,423	32·77	0·113	—	10·0
0·07	—	1·04	0·104	50,641	22·16	0·043	0·42	—
0·07	—	1·04	0·107	47,553	21·22	0·028	0·26	—
0·07	—	0·93	0·114	63,267	28·24	0·046	0·40	—
0·08	—	4·65	0·112	62,581	27·93	0·037	0·33	10·0
0·08	—	4·65	0·120	44,603	19·91	0·039	0·32	19·0
—	0·07	1·74	0·126	63,336	28·27	0·043	0·35	6·0
—	0·07	1·74	0·107	44,877	20·03	0·037	0·35	29·0

to a red heat and hardened in water, but as all of them broke with a less load than 41,172 lbs. per square inch, they

TABLE VII.—RESULTS of EXPERIMENTS on the TENSILE

All the bars tested were filed in the middle to smaller

Those bars preceded by a bracket { were

No. of experiment.	Description of Steel or Iron.	Sample bars.		Section of the bar where it was not filed.		Mean area of the section where filed.
		Carbon.	Phosphorus.	Form.	Diameter or side.	
		per cent.	per cent.		inches.	sq. in.
1	Bessemer steel from Högbo, marked 1·0	1·14	0·018	Round .	0·465	0·1115
2	,, ,, ,, ...	,,	,,	,,	,,	0·0935
3 [2]	,, ,, ,, ...	—	—	,,	,,	0·1252
4 [2]	,, ,, ,, ...	—	—	,,	,,	0·1261
5	,, ,, marked 0·6	0·68	—	,,	,,	0·1135
6	,, ,, ,, ...	,,	—	,,	,,	0·1203
7 [2]	Bessemer iron from Högbo, marked 0·3	0·33	—	Square .	0·348	0·0543
8 [2]	,, ,, ,, ...	,,	—	,,	,,	0·0811
9	,, ,, ,, ...	,,	—	Round .	0·465	0·1069
10	,, ,, ,, ...	,,	—	,,	,,	0·1045
11	Bessemer steel from Carlsdal, marked 0·4	0·42	—	Square .	,,	0·1883
12	,, ,, ,, ...	,,	—	,,	,,	0·1883
13	Uchatius steel from Wikmanshyttan, hardness No. 0·2	1·78	—	Round .	,,	0·1042
14	,, ,, ,,	,,	—	,,	,,	0·1042
15	,, ,, ,,	,,	—	,,	,,	0·1091
16	,, ,, hardness No. 3 ..	0·69	—	,,	,,	0·1014
17	,, ,, ,,	,,	—	,,	,,	0·0968
18	Cast steel from Krupp, marked with one crown	0·62	0·02	,,	,,	0·1299
19	,, ,, ...	,,	,,	,,	,,	0·1261
20	,, ,, ...	,,	,,	,,	,,	0·1187
21	,, ,, ...	,,	,,	,,	,,	0·1141
22	Puddled steel from Surahammar, marked N. P. 1. ..	0·8	—	Square .	,,	0·1956
23	,, ,, ,, ...	,,	—	,,	,,	0·1957
24	,, ,, marked N. H. 1 ..	0·7	—	Round .	,,	0·1233
25	,, ,, ,, ...	,,	—	,,	,,	0·1195
26	,, ,, marked B 2	0·55	—	,,	,,	0·1145
27	,, ,, ,, ...	,,	—	,,	,,	0·1180
28	,, ,, marked N. P. 3 ..	—	—	,,	,,	0·1252
29	,, ,, ,, ...	—	—	,,	,,	0·1203
30	English puddled iron from Low Moor	0·21	0·068	,,	,,	0·1348
31	,, ,, ...	,,	,,	,,	,,	0·1380
32	,, ,, ...	,,	,,	,,	,,	0·1348
33	,, ,, ...	,,	,,	,,	,,	0·1241
34	,, ,, ...	,,	,,	,,	,,	0·1952
35	,, ,, ...	,,	,,	,,	,,	0·1234
36	,, ,, ...	,,	,,	,,	,,	0·1256
37	,, ,, ...	,,	,,	,,	,,	0·1343

[1] Compare

[2] Nos. 3, 4, 7, and 8 did not form part of those ordered

Strength of Iron and Steel at Different Temperatures.

dimensions for a length of from 4 to 6 inches.

originally parts of the same bar.

Breaking weight per sq. inch of the original mean area of the filed part of the bar.		Area of fracture.	Ratio between the area of fracture and the original sectional area of the filed part.	Elongation by rupture		Specific gravity determined after the experiment.			Temperature of the bar during the experiments.	The bar broken in
				Excluding the inch where the fracture took place.	On a length of 5·2 inches, the place of fracture included.[1]	Of the part not filed.	Of the filed part.	Difference between the specific gravities.		
lbs.	tons.	sq. in.		per cent.	per cent.				Fahr.	
140,945	62·92	0·1115	1·00	4·0	4·0	7·8508	7·8491	0·0017	+ 53	Water.
137,034	61·17	0·0747	0·80	3·5	4·3	—	—	—	+330	Paraffin.
115,078	51·37	0·0985	0·79	4·0	5·1	—	—	—	+ 55	Air.
131,032	58·49	0·1137	0·90	5·0	5·5	—	—	—	+356	Paraffin.
126,044	56·27	0·0878	0·77	7·0	8·8	—	—	—	− 40	Alcohol.
123,653	55·20	0·0914	0·76	5·9	8·6	—	—	—	+ 59	Water.
65,286	29·59	0·0148	0·27	5·5	9·4	—	—	—	+ 50	Ditto.
77,677	34·67	0·0344	0·42	5·5	9·2	—	—	—	+350	Paraffin.
77,481	34·59	0·0313	0·29	2·8	8·0	—	—	—	+ 60	Water.
76,422	34·11	0·0389	0·37	6·4	10·3	7·8804	7·8781	0·0023	+320	Paraffin.
76,991	34·37	0·1257	0·67	19·3	21·2	—	—	—	+ 5	Alcohol.
74,589	33·29	0·1299	0·69	15·3	18·1	—	—	—	+ 60	Water.
141,768	63·28	0·1041	1·00	3·3	3·7	—	—	—	− 29	Alcohol.
132,916	59·33	0·1042	1·00	3·1	—	—	—	—	+ 59	Air.
138,818	61·97	0·1060	0·97	2·4	3·9	—	—	—	+282	Paraffin.
114,526	51·12	0·0795	0·78	12·9	—	—	—	—	+ 53	Water.
116,173	51·85	0·0747	0·77	7·5	9·5	7·8431	7·8263	0·0163	+352	Paraffin.
93,666	41·81	0·0731	0·56	7·7	11·5	7·8473	7·8463	0·0010	− 23	Alcohol.
95,793	42·76	0·0878	0·70	10·0	—	7·8465	7·8292	0·0173	+ 57	Water.
95,519	42·63	0·0653	0·55	12·2	15·9	—	—	—	− 20	Alcohol
93,666	41·81	0·0699	0·61	6·7	11·0	7·8435	7·8389	0·0046	+ 50	Water.
123,172	54·98	0·1875	0·96	8·0	—	—	—	—	− 29	Alcohol.
118,300	52·81	0·1656	0·85	10·1	11·5	—	—	—	+ 60	Water.
102,518	45·76	0·0949	0·77	12·7	15·0	7·7783	7·7361	0·0422	+ 55	Ditto.
93,254	41·63	0·1003	0·84	6·8	—	7·7830	7·7600	0·0230	+300	Paraffin.
95,724	42·73	0·1003	0.88	9·3	10·4	—	—	—	− 13	Alcohol.
89,754	40·05	0·0896	0·76	9·7	11·1	—	—	—	+ 57	Water.
73,492	32·80	0·0796	0·63	17·6	21·3	—	—	—	+ 59	Ditto.
70,266	31·35	0·0699	0·58	7·0	9·9	—	—	—	+311	Paraffin.
61,277	27·35	0·0666	0·49	28·8	30·7	—	—	—	− 32	Alcohol.
56,474	25·21	0·0654	0·47	19·0	23·1	—	—	—	+ 68	Water
64,091	28·61	9·0639	0·47	20·4	24·9	—	—	—	− 36	Alcohol.
65,189	29·10	0·0567	0·46	18·9	24·4	—	—	—	+ 59	Water.
64,159	28·64	0·0596	0·50	7·25	10·7	7·7981	7·7456	0·0525	+311	Air.
65,394	29·19	0·0667	0·54	8·25	11·5	—	—	—	+320	Paraffin.
59,081	26·37	0·0624	0·50	15·4	19·4	7·7985	7·7425	0·0460	+ 60	Water.
66,355	29·62	0·0715	0·53	8·75	11·8	7·7930	7·7284	0·0646	+323	Paraffin.

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direct from Högbo, but were purchased in Stockholm.

TABLE VII.—*continued*—RESULTS of EXPERIMENTS on the TENSILE

All the bars tested were filed in the middle to smaller

Those bars preceded by a bracket { were

No. of experiment.	Description of Steel or Iron.	Sample bars. Carbon.	Sample bars. Phosphorus.	Section of the bar where it was not filed. Form.	Section of the bar where it was not filed. Diameter or side.	Mean area of the section where filed.
		per cent.	per cent.		inches.	sq. in.
{ 38	English puddled iron from Low Moor	0·21	0·068	Round .	0·465	0·0823
39	,, ,, ...	,,	,,	,,	,,	0·0807
{ 40	,, ,, ...	,,	,,	,,	,,	0·1062
41	,, ,, ...	,,	,,	,,	,,	0·0784
{ 42	,, from Middlesbrough-on-Tees ..	0·07	0·25	,,	0·581	0·1909
43	,, ,, ..	,,	,,	,,	,,	0·1815
{ 44	,, ,, ..	,,	,,	,,	,,	0·1933
45	,, ,, ..	,,	,,	,,	,,	0·1881
{ 46	,, ,, ..	,,	,,	,,	,,	0·1880
47	,, ,, ..	,,	,,	,,	,,	0·1990
48	,, ,, ..	,,	,,	,,	,,	0·1946
49	,, ,, ..	,,	,,	,,	,,	0·1913
{ 50	Puddled iron from Motala (Sweden)	0·2	0·02	,,	0·465	0·1130
51	,, ,, ...	,,	,,	,,	,,	0·1214
52	,, ,, ...	,,	,,	,,	,,	0·1069
53	,, ,, ...	,,	,,	,,	,,	0·1210
{ 54	,, ,, ...	,,	,,	,,	,,	0·1176
55	,, ,, ...	,,	,,	,,	,,	0·1196
56	,, ,, ...	,,	,,	,,	,,	0·1188
57	,, ,, ...	,,	,,	,,	,,	0·1207
58	,, ,, ...	,,	,,	,,	,,	0·1145
{ 59	,, from Surahammar, N. P.	—	—	,,	,,	0·1169
60	,, ,, ...	—	—	,,	,,	0·1039
61	,, ,, ...	—	—	,,	,,	0·1135
{ 62	Iron made in the charcoal hearth from Åryd (Sweden)	0·07 to 0·18	0·26	Square .	,,	0·1810
63	,, ,,	,,	,,	,,	,,	0·1819
{ 64	,, ,,	,,	,,	,,	,,	0·1373
65	,, ,,	,,	,,	,,	,,	0·1373
66	,, ,,	,,	,,	,,	,,	0·1341
67	,, ,,	,,	,,	,,	,,	0·1326
{ 68 {	Iron made in the Lancashire hearth from Lesjöforss (Sweden)	0·06	0·022	,,	,,	0·1845
69	,, ,,	,,	,,	,,	,,	0·1800
{ 70	,, ,,	0·07	,,	,,	,,	0·1633
71	,, ,,	,,	,,	,,	,,	0·1613
{ 72 [2]	,, ,,	,,	,,	,,	,,	0·1303
73 [2]	,, ,,	,,	,,	,,	,,	0·1199

[1] Compare

[2] Nos. 72 and 73 were taken from the previously broken bar, No. 41 in Table IV., which

Strength of Iron and Steel at Different Temperatures.

dimensions for a length of from 4 to 6 inches.

originally parts of the same bar.

Breaking weight per sq. inch of the original mean area of the filed part of the bar.		Area of fracture.	Ratio between the area of fracture and the original sectional area of the filed part	Elongation by rupture		Specific gravity determined after the experiment.			Temperature of the bar during the experiments.	The bar broken in
				Excluding the inch where the fracture took place.	On a length of 5·2 inches, the place of fracture included.[1]	Of the part not filed.	Of the filed part.	Difference between the specific gravities.		
lbs.	tons.	sq. in.		per cent.	per cent.				Fahr.	
57,366	25·60	0·0401	0·49	23·5	23·8	—	—	—	+ 53	Water.
65,394	29·19	0·0425	0·53	9·0	11·8	7·7833	7·7142	0·0691	+275	Paraffin.
60,316	26·92	0·0567	0·53	20·0	24·2	7·7878	7·7404	0·0474	+ 55	Water.
67,316	30·05	0·0462	0·59	11·5	13·2	7·7889	7·7671	0·0218	+280	Paraffin.
61,483	27·44	0·1177	0·62	24·7	29·2	—	—	—	− 40	Alcohol.
57,846	25·81	0·1060	0·58	19·6	23·9	—	—	—	+ 57	Water.
63,885	28·60	0·1177	0·61	23·1	26·8	—	—	—	− 27	Alcohol.
59,287	26·46	0·1257	0·67	20·8	24·5	—	—	—	+ 59	Water.
52,837	23·58	0·1341	0·71	9·7	12·2	7·6808	7·6033	0·0775	+ 60	Ditto.
55,010	24·60	0·1099	0·55	20·8	24·1	7·6782	7·4807	0·1975	+ 62	Ditto.
69,717	31·12	0·1216	0·62	14·5	17·0	7·6885	7·5646	0·1239	+318	Paraffin.
62,556	27·92	—	—	8·8	10·6	7·6780	7·5629	0·1151	+419	Ditto.
54,141	24·17	0·0513	0·45	21·5	25·8	—	—	—	− 16	Alcohol.
51·121	22·82	0·0626	0·53	16·3	20·8	—	—	—	+ 60	Water.
63,336	28·27	0·0747	0·71	8·1	—	—	—	—	+320	Paraffin.
68,414	30·54	0·0762	0·63	15·7	17·5	—	—	—	+392	Ditto.
68,482	30·57	0·0580	0·49	21·3	24·3	—	—	—	− 27	Alcohol.
50,367	22·48	0·0667	0·56	11·0	—	7·7177	7·6921	0.0256	+ 53	Water.
53,111	23·71	0·0609	0·51	16·3	19·1	7·7359	7·7091	0·0267	+ 60	Ditto.
65,394	29·19	0·0715	0·59	9·6	—	7·7159	7·7065	0·0094	+347	Air.
63,199	28·21	0·0624	0·55	8·0	—	7·7294	7·7032	0·0262	+374	Ditto.
50,710	22·63	0·0654	0·56	16·8	18·5	—	—	—	− 24	Alcohol.
46,310	20·67	0·0413	0·40	11·2	15·2	7·7918	7·7105	0·0813	+ 53	Water.
57,160	25·51	0·0540	0·48	9·7	13·1	7·7762	7·7458	0·0304	+338	Air.
64,159	28·64	0·1257	0·69	18·7	29·9	7·7424	7·6699	0·0725	+ 55	Water.
79,667	35·56	0·1257	0·69	15·7	—	7·7657	7·7114	0·0543	+302	Paraffin.
66,286	29·59	0·0914	0·66	17·3	20·4	—	—	—	− 16	Alcohol.
67,590	30·17	0·1099	0·80	20·9	21·5	—	—	—	− 11	Ditto.
63,130	28·18	0·0654	0·49	14·25	19·5	—	—	—	+ 55	Water.
73,560	32·83	0·0684	0·52	16·5	20·2	—	—	—	+275	Paraffin.
55,376	24·71	0·0684	0·37	22·5	31·6	—	—	—	− 27	Alcohol.
51,053	22·79	0·0624	0·35	27·7	—	—	—	—	+ 60	Water.
44,328	19·78	0·0401	0·25	25·4	33.1	7·8457	7·8135	0·0322	+ 57	Ditto.
62,169	27·79	0·0624	0·39	15·1	20·2	7·8381	7·8339	0·0042	+314	Paraffin.
56,199	25·08	0·0527	0·41	10·7	17·2	—	—	—	+ 55	Water.
62,718	28·00	0·0596	0·49	8·0	11·3	—	—	—	+330	Paraffin.

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accounts for the breaking-load being greater than for the other bars of the same kind of iron.

Table VIII.—Results of Experiments to ascertain in what affected by the Temperature at

The bars tested were each about six feet long, and filed in the

No. of bar.	Description of Steel or Iron.	Treatment of the bars immediately before they were tested.	Amount of carbon: In the bar tested.	Amount of carbon: In bars of the same kind.
			per cent.	per cent.
	Hammered Bessemer steel from Högbo, marked 1.2:—			
1	1st experiment ..	Heated to slight redness and slowly cooled	—	1·35
,,	Same bar .. 2nd ,, ..	Heated ½ hour in paraffine at 266° Fahr.	—	,,
,,	,, .. 3rd ,, ..	Do. do. do.	—	,,
,,	,, .. 4th ,, ..	.. .. ..	—	,,
,,	,, .. 5th ,, ..	.. .. ..	—	,,
,,	,, .. 6th ,, ..	Do. do. 284° F.	—	,,
,,	,, .. 7th ,, ..	Heated for 2 hours in paraffine at 275° Fahr.	—	,,
,,	,, .. 8th ,, ..	.. .. ..	—	,,
,,	,, .. 9th ,, ..	Heated and slowly cooled	—	,,
,,	,, .. 10th ,, ..	.. .. ..	—	,,
,,	,, .. 11th ,, ..	.. .. ..	—	,,
	Hammered Bessemer steel from Högbo, marked with the old No. 3.5:—			
2[1]	1st experiment ..	.. .. ..	1·26	—
,,	Same bar .. 2nd ,, ..	.. .. ..	,,	—
,,	,, .. 3rd ,, ..	.. .. ..	,,	—
,,	,, .. 4th ,, ..	.. .. ..	,,	—
,,	,, .. 5th ,, ..	Heated to slight redness and slowly cooled	,,	—
,,	,, .. 6th ,, ..	Cooled for ½ hour at 9° Fahr.	,,	—
,,	,, .. 7th ,, ..	.. .. ..	,,	—
,,	,, .. 8th ,, ..	.. .. ..	,,	—
	Hammered Bessemer steel from Högbo, marked 0.9:—			
3	1st experiment ..	.. .. ..	—	1·05
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,
,,	,, .. 4th ,, ..	Slightly heated and slowly cooled ..	—	,,
,,	,, .. 5th ,, ..	.. .. ..	—	,,
	Rolled puddled steel from Surahammar, marked B 1:—			
4	1st experiment ..	.. .. ..	0·66	—
,,	Same bar .. 2nd ,, ..	.. .. ..	,,	—
,,	,, .. 3rd ,, ..	.. .. ..	,,	—
,,	,, .. 4th ,, ..	.. .. ..	,,	—
,,	,, .. 5th ,, ..	.. .. ..	,,	—
,,	,, .. 6th ,, ..	.. .. ..	,,	—
	Rolled puddled steel from Surahammar, marked N 1:—			
5	1st experiment ..	.. .. ..	0·56	—
,,	Same bar .. 2nd ,, ..	.. .. ..	,,	—
,,	,, .. 3rd ,, ..	.. .. ..	,,	—
,,	,, .. 4th ,, ..	.. .. ..	,,	—

[1] The bar No. 2 was not filed in the middle, but

[2] This bar had been previously used for other experiments, and

degree the Limit of Elasticity on Stretching Iron or Steel is which the Extension is performed.

middle for a length of about four and a half feet. (See p. 106.)

The original section as to		The filed middle part as to		Average temperature during the experiment.	Difference between the average temperature during the experiment and the previous temperature.	Limits of elasticity.				Elongation of the middle filed part of the bar during each experiment.
						Calculated according to the previous experiments.	Found to be	Consequently		
Form.	Diameter or side.	Length.	Sectional area.					Higher.	Lower.	
	inch.	feet.	square inch.	Fahr.	Fahr.	lbs. per square in.	lbs. per sq. inch.	lbs. per sq. inch.	lbs. per sq. inch.	per cent.
Round.	0·488	4·50	0·1679	+ 62	—	—	61,414	—	—	0·367
,,	,,	,,	,,	+ 68	+ 6	74,109	81,657	7,548	—	0·060
,,	,,	,,	,,	+ 55	− 3	82,481	82,481	0	0	0·081
,,	,,	,,	,,	+264	+109	83,510	79,256	—	4,254	0·027
,,	,,	,,	,,	+ 62	−102	79,873	78,226	—	1,647	0·521
,,	,,	,,	,,	+ 62	0	78,913	76,991	—	1,992	0·065
,,	,,	,,	,,	+266	+204	78,569	91,607	13,038	—	0·030
,,	,,	,,	,,	+ 57	−209	92,842	96,960	4,118	—	0·047
,,	,,	,,	,,	+ 64	—	—	61,758	—	—	0·104
,,	,,	,,	,,	− 2	− 66	72,188	79,736	7,548	—	0·092
,,	,,	,,	,,	+ 55	+ 57	82,344	69,992	—	12,352	0·105
Square.	0·372	5[1]	0·1015[1]	+ 64	—	—	67,833	—	—	0·150
,,	,,	,,	,,	+249	+185	71,158	68,414	—	2,744	0·367
,,	,,	,,	,,	+ 55	−194	70,404	76,579	6,175	—	0·099
,,	,,	,,	,,	+278	+223	77,540	73,766	—	3,774	0·201
,,	,,	,,	,,	+ 59	—	—	65,189	—	—	0·143
,,	,,	,,	,,	+ 46	− 13	66,561	66,561	0	0	0·113
,,	,,	,,	,,	− 11	− 57	67,933	70,678	2,745	—	0·085
,,	,,	,,	,,	+ 50	+ 39	71,364	67,590	—	3,774	0·171
Round.	0·465	4·62	0·1156	+ 57	—	—	64,502	—	—	0·130
,,	,,	,,	,,	− 22	− 79	69,306	72,737	3,431	—	0·126
,,	,,	,,	,,	+ 59	+ 81	—	69,649	—	—	0·204
,,	,,	,,	,,	+269	+210	75,825	85,431	9,606	—	0·171
,,	,,	,,	,,	+ 60	−209	88,176	90,921	2,745	—	0·762
Round.	0·5	4·37	0·1214	+ 57	—	—	46,318	—	—	0·110
,,	,,	,,	,,	− 22	− 79	50,435	53,180	2,745	—	0·187
,,	,,	,,	,,	+ 51	+ 73	57,983	55,239	—	2,744	0·289
,,	,,	,,	,,	+266	+215	62,444	62,444	0	0	0·320
,,	,,	,,	,,	+ 53	−213	68,620	70,335	1,715	—	0·241
,,	,,	,,	,,	+264	+211	72,737	71,364	—	1,363	0.307
Square.	0·476	4·49	0·1561	+ 59	—	—	39,113	—	—	0·303
,,	,,	,,	,,	+275	+216	43,573	46,318	2,745	—	0·324
,,	,,	,,	,,	+ 53	−222	53,043	55,444	2,401	—	0·318
,,	,,	,,	,,	− 27	− 80	56,611	59,013	2,402	—	0·396

was of the same thickness throughout the five feet.
thereby elongated, which accounts for the high limit of elasticity.

TABLE VIII—*continued*—RESULTS of EXPERIMENTS to ascertain in
affected by the TEMPERATURE at

The bars tested were each about six feet long, and filed in

No. of bar.	Description of Steel or Iron.	Treatment of the bars immediately before they were tested.	Amount of carbon: In the bar tested.	Amount of carbon: In bars of the same kind.
			per cent.	per cent.
	Rolled puddled steel from Surahammar, marked N P 2:—			
6[2]	1st experiment ..	.. .. ..	—	0·7
,,	Same bar .. 2nd ,, ..	Heated for ¼ hour in paraffine at 284° Fahr.	—	,,
,,	,, .. 3rd ,, ..	Do. do. at 302° Fahr. ..	—	,,
,,	,, .. 4th ,, ..	Heated for 25 minutes in paraffine at 266° Fahr.	—	,,
,,	,, .. 5th ,, ..	.. .. ..	—	,,
,,	,, .. 6th ,, ..	.. .. ..	—	,,
	Rolled puddled iron from Low Moor:—			
7[2]	1st experiment ..	.. .. ..	—	0·2
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,
	Rolled puddled iron from Motala (Sweden):—			
8	1st experiment ..	.. .. ..	—	0·2
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,
,,	,, .. 4th ,, ..	.. .. ..	—	,,
	Rolled puddled iron from Motala (Sweden):—			
9[2]	1st experiment ..	.. .. ..	—	0·2
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,
,,	,, .. 4th ,, ..	.. .. ..	—	,,
,,	,, .. 5th ,, ..	.. .. ..	—	,,
,,	,, .. 6th ,, ..	Heated to redness and slowly cooled	—	,,
,,	,, .. 7th ,, ..	Heated for ¼ hour in paraffine at 284° Fahr.	—	,,
,,	,, .. 8th ,, ..	.. .. ..	—	,,
,,	,, .. 9th ,, ..	.. .. ..	—	,,
,,	,, .. 10th ,, ..	Heated for ¼ hour in paraffine at 284° Fahr.	—	,,
,,	,, .. 11th ,, ..	.. .. ..	—	,,
,,	,, .. 12th ,, ..	.. .. ..	—	,,
	Rolled puddled iron from Surahammar, marked N H:—			
10	1st experiment ..	.. .. ..	—	0·2
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,
	Rolled iron made in charcoal-hearth at Åryd (Sweden):—			
11	1st experiment ..	.. .. ..	—	0·1
,,	Same bar .. 2nd ,, ..	.. .. ..	—	,,
,,	,, .. 3rd ,, ..	.. .. ..	—	,,

[2] This bar had been previously used for other experiments, and

what degree the LIMIT of ELASTICITY on Stretching Iron or Steel is which the Extension is performed.

the middle for a length of about four and a half feet.

The original section as to: Form.	The original section as to: Diameter or side.	The filed middle part as to: Length.	The filed middle part as to: Sectional area.	Average temperature during the experiment.	Difference between the average temperature during the experiment and the previous temperature.	Limits of elasticity: Calculated according to the previous experiments.	Limits of elasticity: Found to be	Limits of elasticity: Consequently Higher.	Limits of elasticity: Consequently Lower.	Elongation of the middle filed part of the bar during each experiment.
	inch.	feet.	square inch.	Fahr.	Fahr.	lbs. per square in.	lbs. per sq. inch.	lbs. per sq. inch.	lbs. per sq. inch.	per cent.
Square.	0·488	4·50	0·2163	+ 62	—	—	52,151[2]	—	—	0·106
,,	,,	,,	,,	+ 62	0	62,444	68,276	5,832	—	0·044
,,	,,	,,	,,	+ 57	− 5	71,776	71,776	0	0	0·048
,,	,,	,,	,,	+ 68	+ 11	72,599	72,051	—	548	0·066
,,	,,	,,	,,	+237	+169	74,795	68,620	—	6,175	0·079
,,	,,	,,	,,	+ 64	−173	69,992	71,707	1,715	—	0·082
Round.	0·5	4·72	0·1256	+298	—	—	41,515[2]	—	—	0·476
,,	,,	,,	,,	+ 51	−247	42,201	46,318	4,117	—	0·986
,,	,,	,,	,,	− 16	− 67	48,377	50,435	2,058	—	0·179
Round.	0·476	4·65	0·1229	+ 57	—	—	34,172	—	—	0·256
,,	,,	,,	,,	+267	+210	36,368	34,035	—	2,333	0·571
,,	,,	,,	,,	+ 57	−210	35,339	39,662	4,323	—	0·151
,,	,,	,,	,,	+278	+221	40,142	35,339	—	4,803	0·705
Round.	0·476	4·49	0·1112	+284	—	—	34,447[2]	—	—	0·276
,,	,,	,,	,,	+ 57	−227	35,819	39,250	3,431	—	0·374
,,	,,	,,	,,	+275	+218	39,799	35,270	—	4,529	0·379
,,	,,	,,	,,	+ 64	−211	37,260	42,132	4,972	—	0·978
,,	,,	,,	,,	− 5	− 69	42,544	45,289	2,745	—	0·230
,,	,,	,,	,,	+ 60	—	—	27,448	—	—	0·294
,,	,,	,,	,,	+ 64	+ 4	28,134	31,565	3,431	—	0·484
,,	,,	,,	,,	+264	+200	33,344	29,369	—	3,975	0·276
,,	,,	,,	,,	+ 60	−204	29,918	33,898	3,980	—	0·161
,,	,,	,,	,,	+ 64	+ 4	34,653	33,966	—	687	0·093
,,	,,	,,	,,	+271	+207	34,653	29,849	—	4,804	0·390
,,	,,	,,	,,	+ 66	−195	30,535	34,653	4,118	—	0·935
Round.	0·476	4·50	0·1269	+ 57	—	—	28,134	—	—	0·103
,,	,,	,,	,,	− 18	− 75	29,506	32,594	3,088	—	0·256
,,	,,	,,	,,	+300	+318	35,956	28,820	—	7,136	0·138
Square.	0·511	4·49	0·2087	+ 53	—	—	45,426	—	—	0·358
,,	,,	,,	,,	− 22	− 75	46,455	49,886	3,431	—	0·630
,,	,,	,,	,,	+ 50	+ 72	50,092	47,347	—	2,745	0·328

thereby elongated, which accounts for the high limit of elasticity.

TABLE IX.—RESULTS of EXPERIMENTS for DETERMINING the MODULUS

No. of the bar.	Description of Iron or Steel.	Specific gravity of the bar.	Amount of carbon: In the bar tested.	Amount of carbon: In bars of the same kind.	Section as to[1]: Form.	Section as to[1]: Mean area before the experiment.	When the bar has not been heated.	The bar had just before the modulus was taken obtained a permanent elongation of
			per cent.	per cent.		square inch.	lbs. per square inch.	per cent.
1	Hammered Bessemer Steel from Högbo—Marked 1·2	7·832	—	1·35	Round.	0·1823	—	—
2[3]	,, with the old number of hardness 3·5. The bar No. 2 Table VIII.	7·850	1·26	—	Square.	0·1015	30,124,180	0·004
3	,, 0·9. The bar No. 3 in Table VIII.	7·849	—	1·05	Do.	0·1156	30,604,520	0·014
4[3]	Hammered Bessemer Iron from Högbo—Marked with the old number of hardness 5	7·878	0·1	—	Do.	0·1003	32,320,020	0·002
5		7·879	0·15	—	Do.	0·1107	34,241,380	0·001
6	Rolled Cast-steel from Wikmansbyttam—Degree of hardness No. 1	7·832	1·22	—	Round.	0·1691	31,222,100	0·021
7	Hammered Cast-steel from F. Krupp—Marked with two crowns	7·843	—	0·61	Do.	0·2065	31,359,340	0·0008
8	Rolled Puddled Steel from Surahammar—Marked B 1. The bar No. 4 in Table VIII.	7·781	0·66	—	Square.	0·1214	—	—
9	Marked N 1. The bar No. 5 in Table VIII.	7·828	0·56	—	Do.	0·1561	29,918,320	0·027
10	Rolled Puddled Iron—From Low Moor	7·780	—	0·20	Round.	0·1961	31,976,920	0·006
11	,, Dudley	7·463	—	0·09	Do.	0·1844	28,408,680	0·008
12	,, ,, ...	7·444	—	0·09	Do.	0·2006	27,448,000	0·077
13	,, Motala (Sweden)	7·734	0·05	—	Do.	0·1942	30,261,420	0·008
14	,, ,, ,, The bar No. 8 in Table VIII.	7·734	—	0·2	Square.	0·1229	29,575,220	—
15	From Surahammar, marked N	7·789	0·14	—	Do.	0·2176	31,084,860	0·018
16	,, ,, ,, N H. The bar No. 10 in Table VIII.	7·807	—	0·2	Do.	0·1269	30,467,280	0·002
17	Rolled Iron made in charcoal-hearth—From Åryd (Sweden). The bar No 11. in Table VIII.	7·780	—	0·07 to 0·18	Do.	0·2087	26,761,800	0·037
18	,, ,, ,, ,,	7·761	—	Do.	Do.	0·2279	27,791,000	0·003
19	Rolled Iron made in charcoal-hearth—From Hallstahammar (Sweden)	7·829	—	0·07	Do.	0·1891	28,957,640	0·013
20	,, ,, ,, ...	7·854	—	0·07	Do.	0·1965	30,810,380	0·001

[1] For the bars in Table VIII., which were filed to smaller dimensions in the middle, this table shows only the form and the
[2] The influence of the permanent elongation on the modulus of elasticity was first examined after the bar had been heated,
[3] The bars Nos. 2, 4, and 5, were not ordered at Högbo, but were purchased in Stockholm.

of ELASTICITY in Iron and Steel by TRACTION.

The Modulus of Elasticity

When the bar had been heated to slight redness.	The bar had just before the modulus was taken obtained a permanent elongation of	Diminished by the bar having undergone permanent elongation.	The permanent elongation which the bar had obtained shortly before.	Diminution.	By an increase of temperature. From	By an increase of temperature. To	Diminished on an average for an increase of temperature of 1·8°F=β	Increase.	By reduction of the temperature. From	By reduction of the temperature. To	Increase on an average for a decrease of temperature of 1·8° F.=β.
lbs. per square inch.	per cent.	per cent.	per cent.	per cent.	Fahr.	Fahr.	per cent.	per cent.	Fahr.	Fahr.	per cent.
31,839,680	0·003	6·4[2]	0·58	—	—	—	—	0·5	+50	− 9	0·015
30,535,900	0·006	4·9[2]	0·66	3·8	+55	+271	0·031	1·0	+48	− 22	0·025
31,496,580	0·000	9·24[2]	0·72	—	—	—	—	—	—	—	—
34,584,480	0·017	6·5	0·61	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	8·6	0·7	4·2	+60	+275	0·035	—	—	—	—
32,114,160	0·004	6·2	0·78	3·8	+59	+264	0·033	1·2	+50	− 11	0·035
30,330,040	0·015	—	—	—	—	—	—	2·1	+51	− 27	0·047
—	—	5·7	0·16	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—
—	—	6·6	1·77	—	—	—	—	—	—	—	—
30,779,000	0·001	7·76	0·72	—	—	—	—	—	—	—	—
—	—	—	—	5·0	+59	+284	0·040	1·9	+48	− 25	0·046
—	—	—	—	—	—	—	—	—	—	—	—
30,741,760	0·003	—	—	—	—	—	—	—	—	—	—
—	—	4·3	0·54	—	—	—	—	2·0	+55	− 25	0·044
29,232,120	0·003	0·78	0·32	—	—	—	—	—	—	—	—
—	—	—	—	3·7	+59	+262	0·033	—	—	—	—
30,810,380	0·000	—	—	—	—	—	—	—	—	—	—

mean area.
and hence the per centage diminution of the modulus which is here given should be referred to the value obtained after heating.

Table X.—Results of Experiments to determine the

N.B. All the bars tested had a length of 4·3 feet

No. of experiment.	Description of Iron or Steel.	Specific gravity of the bar.[1]	Amount of carbon: In the bar tested.	Amount of carbon: In bars of the same kind.	Sectional area of bars not filed: Form.	Sectional area of bars not filed: Diameter or side.	Sectional area of bars filed. Rectangular section: Average width.	Sectional area of bars filed. Rectangular section: Average height.
			per cent.	per cent.		in.	in.	in.
	Hammered Bessemer steel from Högbo—							
1	Marked 1·0	7·868	—	—	—	—	0·48	0·4890
2[2]	Marked with the old No. of hardness 3·5, the bar No. 2 in Table IX.	7·850	1·26	—	—	—	0·3097	0·3165
	Hammered Bessemer iron from Högbo—							
3[2]	Marked with the old No. of hardness 5, the bar No. 5 in Table IX.	7·879[3]	0·15	—	—	—	0·3476	0·3473
	Rolled Bessemer steel—							
4	From Carlsdal	—	0·99	—	Square	0·4651	—	—
	Rolled puddled steel from Surahammar—							
5	Marked N 1, the bar No. 9 in Table IX.	7·828	0·56	—	—	—	0·3629	0·4029
6[2]	,, B 1, the bar No. 8 in Table IX.	7·781	0·66	—	—	—	0·3469	0·3474
7	,, P 1	—	—	0·7	Square	0·4651	—	—
	Rolled puddled iron—							
8	From Low Moor	7·780	—	0·2	Round	0·5	—	—
9	From Middlesbrough-on-Tees	—	—	0·97	Ditto	0·6162	—	—
10	The stem of a rail from Cwm Avon in Wales, cut out by a planing machine, and heated and rolled to a bar	7·597	—	—	—	—	0·4523	0·5009
	Rolled puddled iron—							
11[2]	From Motala. The bar No. 14 in Table IX.	7·734	—	0·2	—	—	0·3238	0·3251
12	From Surahammar, marked N. The bar No. 15 in Table IX.	7·789	0·14	—	—	—	0·4588	0·4702
13[2]	From Surahammar, marked N H. The bar No. 16 in Table IX.	7·807	—	0·2	—	—	0·3473	0·3483
	Rolled iron made in charcoal hearth—							
14	From Åryd. The bar No. 17 in Table IX.	7·780	—	0·1	—	—	0·4513	0·4533
15[2]	,, ,, 18 ,,	7·761	—	0·1	—	—	0·4791	0·4690
16	From Hallstahammar. The bar No. 19 Table IX.	7·829	—	0·07	—	—	0·4052	0·4520
17[2]	From Hallstahammar. The bar No. 20 Table IX.	7·854	—	0·07	—	—	0·4263	0·4584

Remarks.—The bars Nos. 1, 2, and 3 were not ordered from Högbo, but were bought in Stockholm.

The bar No. 2, which after annealing gave a modulus of elasticity of 30,535,900 lbs., on stretching was tested by bending in two directions at right angles to each other. The modulus of elasticity was 31,908,300 lbs. in the one case, and 31,565,200 lbs. in the other. The bar was again annealed, but the modulus was not increased to more than 32,388,640 lbs. per sq. in.

[1] The specific gravity was taken when

[2] The bars Nos. 2, 3, 6, 11, 13, 15, and 17, had been

[3] By annealing, the specific gravity

Modulus of Elasticity in Iron and Steel by Flexion.

each, the distance between the supports being 4 feet.

The modulus of elasticity.												
When the bar had not been heated.	When the bar had been heated.	Decrease by the permanent deflection of the bar.	The permanent deflection which the bar had obtained immediately before.	Decrease through hardening.	Decrease.	By increase in the temperature. From	To	Average diminution by an increase of temperature of 1·8° F. $=\beta_1$.	Increase.	By reduction of temperature. From	To	Average increase by reduction of temperature of 1·8° F. $=\beta_1$.
lbs. per sq. inch.	lbs. per sq. inch.	per cent.	in.	per cent.	per cent.	Fahr.	Fahr.	per cent.	per cent.	Fahr.	Fahr.	per cent.
30,760,346	—	1·55	0·1476	1·0	1·98	+59	+266	0·017	0·64	+57	0	0·020
—	31,908,300	—	—	—	—	—	—	—	—	—	—	—
—	32,388,640	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	3·2	—	—	—	—	1·12	+57	+2	0·036
29,232,120	30,741,760	—	—	1·1	3·28	+51	+269	0·027	1·44	+57	+2	0·046
—	30,673,140	—	—	—	—	—	—	—	1·20	+59	−2	0·035
—	—	—	—	1·6	2·18	+60	+257	0·020	0·48	+50	+14	0·024
—	—	—	—	—	—	—	—	—	0·95	+66	+9	0·030
—	—	—	—	—	—	—	—	—	1·02	+60	+5	0·033
27,310,160	27,379,380	—	—	—	—	—	—	—	1·33	+66	+5	0·040
—	29,849,700	—	—	—	—	—	—	—	1·14	+66	0	0·031
30,810,380	30,810,380	1·88	0·4476	—	2·60	+57	+273	0·022	0·96	+55	−2	0·030
—	31,839,680	—	—	—	—	—	—	—	0·99	+66	+11	0·032
27,585,240	27,585,240	1·47	0·0813	—	4·06	+57	+260	0·036	1·18	+57	+2	0·038
—	27,516,620	—	—	—	—	—	—	—	—	—	—	—
31,084,860	31,290,720	0·70	0·7034	—	—	—	—	—	1·11	+66	0	0·030
—	30,398,660	—		—	—	—	—	—	—	—	—	—

The bar No. 13 was bent throughout the whole of its length, and straightened again. The modulus of elasticity was thus decreased 6·6 per cent.

The modulus of elasticity of the annealed bar No. 15 on flexion was first 27,379,350 lbs., and by repeated annealing did not increase to more than 27,516,620 lbs. per sq. in.

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the bars were in their original state.
heated immediately before the experiments.
was increased to 7·882.

APPENDIX

BY THE TRANSLATOR.

1. Introduction. — 2. Experiments on Iron exposed to sudden shocks at different Temperatures, the elasticity of the supports remaining constant or nearly so. — 3. Results of the experiments. — 4. Conclusions. — 5. Probable cause of these results. — 6. Steel *versus* Iron.

1. *Introduction.*

ALTHOUGH the extensive series of experiments conducted by the Swedish Government Committee (consisting of Messrs. Ekman, Styffe, and Grill), and described by the author in the previous pages, had for their *special* object, to determine the value of Swedish raw material for the manufacture of railway plant,—such as rails, axles, wheels, tyres, springs, &c.,—yet considering the accuracy with which these experiments were performed, their reference to materials obtained from other countries, and the value of the conclusions to which they led, the translator has been induced to regard them as worthy of attention not only by railway engineers in general, but also by manufacturers of iron and steel.

At the present time, when "Steel *versus* Iron" is the great engineering question of the day, it becomes of special importance to collect all information tending to throw light upon the subject, when founded upon experience, and free from partiality. In considering whether steel should be substituted for iron, certain objections have long been brought forward, especially in those countries which suffer from a severe climate, such, for instance, as the Scandinavian Peninsula, Russia, Canada, and the northern part of America.[1] On this point the author has, by

[1] The general objection to the use of steel as a substitute for iron, is the want of uniformity in the manufacture. If steel could be depended upon in regard to strength, elasticity, &c., it would shortly take the place of iron at a considerably increased price.—W. FAIRBAIRN.

his elaborate experiments, arrived at certain remarkable results which run directly counter to the general belief—results which show indeed that iron and steel are, if anything, actually stronger when exposed to severe cold than at ordinary temperatures. This was found to be the case in several experiments where iron and steel were tested as to extensibility, strength, and resistance to flexure. The author cannot, however, deny the fact that iron as well as steel when employed as railway material, and consequently exposed to sudden concussions, breaks more frequently during extreme cold than at ordinary temperatures; but he explains this fact by referring to the diminished elasticity of the supports on which the metal rests.[2] The author also admits that it is just when exposed to the most intense cold that fracture most commonly occurs; but this too he refers to the same cause, and concludes from his experiments on the elasticity of a wet wooden sleeper, that on a reduction of temperature from 35° to 2° F. the elasticity of the ground would be diminished by twelve per cent. (see page 113). From these experiments the author considers that the only means to prevent accidents on railways exposed to a severe climate is either to lessen the speed during winter or to give the rolling stock more elasticity by employment of india-rubber springs or otherwise.

In the winter of 1865, which was the first during which express trains were run between Stockholm and Gothenburg, an accident occurred which threatened to cast a mantle of mourning over the whole of Sweden. One morning in January,

[2] It does not appear that rigid supports, such as frozen ground, constitute the sole cause of the deterioration of iron and steel at a low temperature. It would operate to a small extent, but not sufficiently to account for the limited power of resistance as shown in the Table (p. 162 *et seq.*) at low temperatures. There is doubtless a molecular change in the material between the extremes of high and low temperatures, but even these are not considerable, as may be seen by my own experiments. It will be observed that these experiments commenced at a temperature of 30° below the freezing point of Fahr. up to 212° and 435° consecutively, and also to a red heat perceptible in daylight. Throughout all these changes, the *tensile* strength of plates and bar-iron was not seriously injured, and gave widely different results from those obtained in your case by *impact.* From this it would appear, that the *tenacity* of iron bars and plates is not seriously injured at a temperature as high as 435°, which is the maximum tensile strength, nor do they appear to suffer to any great extent when the temperature is reduced to 30° Fahr. At this temperature the *elasticity* is however considerably impaired, and much greater risk is incurred if subjected to vibratory action or a series of *impacts.* See paper 'On the Tensile Strength of Wrought Iron at various Temperatures,' published in the 'Transactions of the British Association for the Advancement of Science,' for 1856, p. 405.—W. FAIRBAIRN.

when the thermometer stood at − 20° F., His Majesty King Charles XV. left Stockholm by the ordinary express train. After proceeding for some hours at the speed of about 35 miles an hour, the tyre of one of the wheels under the royal carriage broke in three pieces, and the carriage having left the rails was dragged along the ballast for a considerable distance. Providentially no one was injured. Two days afterwards at a similar temperature another accident occurred also through a broken tyre, but fortunately was attended by no serious result beyond the shock given to a postmaster, who was in the mail-van, which rolled down a steep embankment. The occurrence of a third and similar accident, also during this severe weather, induced the railway authorities to decide on slackening the speed during the winter months to about 25 miles per hour; and since then no accident of that kind has occurred. The tyres which broke in these cases were of iron, made in England, and were fastened with bolts to ordinary iron wheels. Wooden disc-wheels have since been adopted with solid tyres, or without weld; and at the same time india-rubber springs have been introduced between the frame and the body of the carriages: these improvements have considerably increased the comfort of the passengers, and have prevented the occurrence of further accidents. It is remarkable that the three above-mentioned accidents should all have happened on the very days when the cold was severest, viz. − 20° F., but that none occurred during a frost in which the thermometer did not fall below 5° F.—a temperature by no means rare during several consecutive weeks in a Swedish winter.

In order to investigate the cause why iron in cases such as those just cited, is disposed to break more readily when subjected to blows during extreme cold than at ordinary temperatures, and in order to determine how far this is really due to diminished elasticity of the supports, and how far to increased brittleness in the metal itself, the translator proposed to the Royal Administration of Government Railways the execution of some experiments on a large scale and in a simple but practical manner. As the results of these investigations have already been given (note to page 114), the translator will now record the full details of these experiments, which tend to contradict some of the author's conclusions, as mentioned above.

2. *Experiments on Iron exposed to sudden Shocks at different Temperatures, the Elasticity of the Supports remaining constant or nearly so.*

Having been charged by the Royal Administration aforesaid with the execution of these experiments, the translator submitted his proposed *modus operandi* to the author. The greatest difficulty was to find supports which would not be affected by differences of temperature. It was assumed, however, that the elasticity of granite would not vary within the range of temperature between a hot summer and a cold winter day; or at least not to an extent sufficient to vitiate the results of the experiments. Accordingly the translator conducted his investigations in the following manner:—A granite rock near Stockholm was levelled *in situ*, and upon this plane surface two cubic blocks of granite, each containing about ten cubic feet, were placed four feet apart, to serve as supports. A ball, weighing 9 cwt., was so adjusted that it could be raised to a height of 15 feet, and then allowed to fall on the rail, midway between the supports.[3] The bars tested were iron rails from the Aberdare Works in South Wales, and from Le Creusot in France—all bars being of exactly the same section, and made under the superintendence of the translator. Each rail was of Vignole's section, weighing 66 lbs. per yard, and measuring 4¾ inches high and 4 inches broad at the base. Two rails made in Belgium at the works of Messrs. Dorlodot were also tested, but these were of a lighter construction, weighing only about 50 lbs. per yard. All the rails were tested by the ball falling from a height of 5 feet for the first blow, with an increase of 1 foot for each succeeding blow until fracture occurred; the deflection being measured after each impact. A small piece of wrought iron was placed on the top of each rail-head so as to concentrate the effect of the blow, within a width of 1½ inch. Each rail was first broken in the middle, and both halves (each 10·5 feet in length) were marked with the same number. Comparative experiments were then instituted with these halves, one being tested during the most severe cold of winter, and the other on a hot summer day, the average temperature during the former

[3] I may mention that all rigid supports are objectionable for the supports of railway bars, and that a compressible and elastic substance, such as wood bedded on earth is infinitely superior to stone-blocks, as the timber and porous earth act as a cushion to the rolling load. Many hundreds of miles laid with stone blocks had to be replaced with wood-sleepers at the commencement of railways.—W. FAIRBAIRN.

experiment being 10° F., and during the latter 84° F. Unfortunately the winter was so far advanced when these experiments were commenced that the temperature never fell below 10° F.[4] Some of these rails were also tested in a similar manner at a temperature of 35° F.

The first part of the investigation was conducted under the personal superintendence of the translator, assisted by a foreman in the Government Railway Service. The latter part of the investigation (or the series of summer experiments) was, however, conducted by this foreman, in the absence of the translator, who was occupied in England during the entire summer on Government business. He has, however, every reason to believe that the experiments made in his absence are worthy of reliance. The Table on p. 162 *et seq.* gives the full details of these experiments, showing the length and quality of each rail, the number of blows delivered, the height of the fall of the ball, the deflection produced by each blow until fracture occurred, and the temperature at which the experiments were severally made. On examining this table, the first result which strikes the observer is the great variation in strength exhibited by different rails when broken in the middle. For example, Rail No. 4 broke at the first blow by a 5-feet fall, whilst another rail from the same works, No. 5, resisted five blows, each with an increasing height of one foot in the falling ball. Such a difference will, however, be easily understood by those practically acquainted with the manufacture of rails, when they remember how often the quality of the iron varies even in the same works, and how much it is influenced by the length of time the pile is kept in the furnace, and its liability to be over-heated if left there too long; all these causes having a tendency to make the rails differ widely in strength. It may nevertheless be fairly assumed that one-half of a rail will not differ to any great extent from the other half of the *same* rail; and it is on this assumption that the value of these experiments is based. To those, however, who urge that there may be a difference even in the same rail, it may be said that the great number of bars tested (namely, seven from Aberdare, five from Creusot, and two from Dorlodot's) would still give an average result sufficient to lead to

[4] In Sweden and Norway, and all northern countries where the winters are severe, double thickness in the wood-sleepers would offer increased security to the rails, and remove the jar or vibrating motion from the rails and the rolling load. —W. FAIRBAIRN.

definite conclusions. The total height expressed in feet from which the ball fell before each rail broke may therefore serve as a comparative numerical expression for the resistance and strength exhibited in these experiments.

3. *Results of the Experiments.*

From the details given in the Table on p. 162 *et seq.*, we deduce the totals, shown in the following tabular form :—

TOTAL HEIGHT of the FALL of the BALL, required to break each Rail at different Temperatures.

Works where the Rails were made.	No. of Rails tried.	Rails 21 Feet long.			Rails 10·5 Feet long.		
		Temperature, F.			Temperature. F.		
		84°	35°	10°	84°	35°	10°
		Total Height of Fall in Feet.					
Aberdare (Wales)	1	..	11	..	45	26	..
,, ,, ...	2	..	11	..	56	26	..
,, ,, ...	3	..	18	..	35·5	11	..
,, ,, ...	4	..	5	..	45·3	5	..
,, ,, ...	5	..	45	..	56	..	18
,, ,, ...	6	..	..	11	56	..	5
,, ,, ...	7	..	..	5	35	..	5
Le Creusot (France) ..	1	..	26	..	45	..	26
,, ,, ...	2	..	18	..	35	..	11
,, ,, ...	3	..	11	..	35	..	18
,, ,, ...	4	..	35	..	45	..	11
,, ,, ...	5	..	26	..	35	..	5
Dorlodot's (Belgium) ..	1	..	..	4	22	..	9
,, ,,	2	..	..	4	30	..	4
Average of—							
7 English Rails ..	..	..	18	8	49·6	17	9·3
5 French do.	..	..	23·2	..	39	..	14·2
2 Belgian do.	..	..	..	4	26	..	6·5
Average of— 3 English Rails .. 5 French do. .. .. 2 Belgian do.	..	..	..	..	39	..	11

Thus the average results obtained from ten rails show that one end of a bar tested at 84° F. resisted a blow from the *height of* 39 *feet*, whilst the other end, tested at 10° F., only sustained a blow from the *height of* 11 *feet.*

This table gives the number of each rail, the total fall in feet by which the rail was first broken in two, and the resistance of each half thus obtained when tested at different temperatures. The total of the results for each kind of rail divided by the number examined gives the average for each make, as shown in the lower part of the table. The results thus obtained show that when the elasticity of the supports remained constant, the same rails tested by sudden shocks at temperatures of 84° F. and 10° F. exhibited differences in strength which may be expressed by the numbers 39 and 11 respectively; these figures representing the total height in feet of the falling ball which the two halves of each rail resisted when tested, the one at 84° F., the other at 10° F.

4. *Conclusions.*

From these experiments the translator is led to draw the following conclusions:—

1. That for such iron as is usually employed for rails in the three principal rail-making countries (Wales, France, and Belgium), the breaking strain, as tested by sudden blows or shocks, is considerably influenced by cold; such iron exhibiting at 10° F. only from one-third to one-fourth of the strength which it possesses at 84° F.
2. That the ductility and flexibility of such iron is also much affected by cold; rails broken at 10° F., showing on an average a permanent deflection of less than one inch, whilst the other halves of the same rails, broken at 84° F., showed a set of more than four inches before fracture.
3. That at summer-heat the strength of the Aberdare rails was 20% greater than that of the Creusot rails; but that in winter the latter were 30% stronger than the former.

5. *Probable Cause of the Results obtained by Experiments on Concussion at different Temperatures.*

We have long been familiar with the term "cold-short" as applied to iron, and have supposed that the presence of phosphorus induces this property by rendering the metal extremely

brittle when exposed to cold.[5] The experiments just described were certainly made with cold-short iron (unfortunately the amount of phosphorus was not determined, but rails from Cwm Avon were found to contain 0·24% of phosphorus, as shown on p. 132), and it is therefore not improbable that the phosphorus generally present in iron rails may have given rise to the apparent contradiction between the translator's results and those deduced from previous experiments made by the author. It should, however, be remembered that the translator's results were obtained by sudden shocks, whilst the author's experiments were on gradual bending and stretching; so that the two results are not fairly comparable. It is only when the author applies *his* experiments to railway materials (which from their position are necessarily exposed to sudden shocks), and thence concludes that such materials are more subject to fracture in winter than in summer, *solely through a difference of elasticity in the supports*, that the translator feels compelled to differ from him. Although the experiments on which the translator grounds this opposition were made with a somewhat rude arrangement, yet they clearly show that at any rate such iron as that generally used for rails is in its resistance to blows influenced to a very great extent by cold. Had the iron been free from phosphorus, or nearly so, it is highly probable that different results would have been obtained. It is also to be regretted that the effect of temperature on the strength of superior kinds of iron and *steel* was not determined at the time the experiments were made; no steel rails had, however, been then imported into Sweden.

6. *Steel* versus *Iron*.

It may be seen from the author's experiments, as well as from his conclusions, that for the most important articles steel is recommended in preference to iron; and for countries which, like Sweden, suffer from severity of climate, the author recommends a *mild steel*, not only for railway materials but also for ship-plates, bridges, girders, boilers, and indeed for nearly all the

[5] No doubt phosphorus and sulphur may account for the loss of strength indicated in these experiments, but is inconclusive unless the quantity is determined. —W. FAIRBAIRN.

principal articles of ordinary iron-manufacture. The author justly says that it is only in consequence of its high price that steel has hitherto been retarded in its advance as a substitute for iron; but now, through the invention of the Bessemer process and the great progress it has recently made, this obstacle is removed to a very great extent.

In these remarks the translator fully concurs, and he has therefore united, in Plate IX., the two Plates III. and IV.; and has drawn with black lines all the curves showing the tensile strength of Bessemer and cast steel, leaving the other curves in dotted lines.

From this table it may be easily seen that the Bessemer material is capable of standing nearly the same test of tensile strength as any other steel—whether made by puddling, by charcoal-refining, or by the cast-steel process—provided that the raw material is equally free from phosphorus, and that the product obtained has the same degree of hardness, or in other words contains the same proportion of carbon. The curves run very nearly parallel from the hardest steel with 1·2% of carbon to the softest iron with 0·2%, although the product might have been made by different processes, in different countries, and from different raw materials. In the properties of iron or steel made by dissimilar methods there may be slight differences as to soundness and homogeneity, which are not shown by these experiments. In this respect, however, Bessemer steel and cast-steel are certainly preferable to iron or puddled material, since this is seldom free from welding-joints.

On this point the translator would only remark that all the *Bessemer steel*, the results of which are represented in curves on the plan, was made from pure Swedish charcoal pig-iron, which contained but a very small proportion of such impurities as phosphorus and sulphur, and only about 1% of silicon. It has lately been observed in several works in England that the action of silicon is similar to that of carbon in giving hardness to steel. The same thing has also been found in practice in Austria, for on changing the raw material from charcoal to coke pig-iron the steel acquired hardness and brittleness (see Professor Tunner's letter to Dr. Percy in a paper "On the Manufacture and Wear of Rails."—*Proc. Inst. Civ. Engineers*, 1868).

All the pig-iron used in England and in Westphalia for the Bessemer process is made by coke from Hæmatite ore, and contains on an average 2·5% of silicon. Although the amount of

impurities in the shape of phosphorus and sulphur is not greatly in excess of that present in charcoal pig-iron, yet the steel produced from the coke iron is not equal in quality to that made from charcoal iron. As long therefore as any abundance of charcoal pig-iron may be obtained in the market at an advanced price of not more than 20*s.* per ton—whether from Canada, Nova Scotia, Sweden, or Norway—it would be bad policy for manufacturers of steel by the Bessemer process to allow so slight a difference in the cost of the raw material to affect their considerations, especially when manufacturing superior articles—such as shafts, axles, tyres, girders, plates, &c. For rails, however, coke pig-iron is sufficiently good if properly converted in the Bessemer vessel. The choice of raw material is of more importance for the Bessemer process than for any other mode of manufacture, since the impurities are not carried off to the same extent by that process as they are, for example, by puddling. It may be of interest to mention that even with the Swedish charcoal pig-iron the best qualities yield a superior steel by the Bessemer, as well as by all other processes. The Dannemora iron, for example, has yielded a Bessemer steel, which has been tested in Sheffield for use in cutlery with the most satisfactory results, and found superior to the Bessemer steel made from ordinary brands of Swedish pig-iron.

The continued reduction in the price of Bessemer and cast-steel by improvements in their manufacture is certainly of the greatest benefit to the world. Indeed, there is every reason to believe that ere long we shall obtain Bessemer steel for the same price as iron, and thus avoid all want of homogeneity from welding-joints and other causes; the only difference being an addition of about 20*s.* per ton in the price of the pig-iron employed, for the fuel and labour expended in the Bessemer process have already been reduced to the same as, or even to less than, their cost by either the puddling or the finery process.

For the determination of the carbon, silicon, sulphur, phosphorus, and other constituents of steel, there are already many new methods in successful operation at the different steel works; nearly all of them now possessing a laboratory and a chemist of their own, which is but seldom the case at iron works. Still it behoves the consumer to pay much more regard to a thorough examination of the character of the steel which he receives, and not to be led away by mere lowness of price; for the loss resulting from a single accident due to inferior

metal may far exceed the amount saved in the difference ot cost between good and bad material. Having himself no interest to advance in advocating the employment of either one or the other material, the translator is disposed to think that the author's experiments, performed as they were with the greatest accuracy, skill, and impartiality, and at the expense of a foreign Government, may not be without interest to the manufacturers, as well as to the consumers of iron and steel in this country. He therefore indulges the hope that his task of translating the work into the English language may not be altogether in vain. At the same time he solicits the indulgence of the public for the errors that he may unwittingly have committed, and begs in conclusion to tender his sincere thanks to Dr. Percy and Dr. Fairbairn for their valuable assistance.

TABLE TO THE APPENDIX.

Experiments with Rails, tested by a Falling Weight at different Temperatures, conducted by the Translator for the Swedish Government Administration, Stockholm. 1867.

	No. of blows.	Height of fall of the ball in feet.	Permanent deflection.	Broke.	Temperature. Deg. Fahr.
Aberdare rail No. 1. 21 ft. long ..	1	5	1		35
,, ,, ..	2	6	..	Broke	,,
One half of the same rail	1	5	1		,,
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{3}{4}$		,,
,, ,, ...	4	8	..	Broke	,,
The other half of the same rail	1	5	$\frac{7}{8}$		84
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{3}{4}$		,,
,, ,, ...	4	8	$4\frac{1}{4}$		,,
Became twisted and could not be tested	5	9	$5\frac{1}{2}$		,,
further	6	10	6	Broke	,,
Aberdare rail No. 2. 21 ft. long ..	1	5	$\frac{1}{2}$		35
,, ,, ..	2	6	..	Broke	,,
One half of the same rail	1	5	$\frac{3}{4}$		,,
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{3}{4}$		,,
,, ,, ...	4	8	..	Broke	,,
The other half of same rail	1	5	$\frac{7}{8}$		84
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{7}{8}$		,,
,, ,, ...	4	8	4		,,
,, ,, ...	5	9	$5\frac{1}{4}$		,,
,, ,, ...	6	10	$6\frac{3}{4}$		,,
,, ,, ...	7	11	..	Broke	,,
Aberdare rail No. 3. 21 ft. long ..	1	5	$\frac{1}{2}$		35
,, ,, ..	2	6	1		,,
,, ,, ..	3	7	..	Broke	,,
One half of same rail	1	5	$\frac{3}{4}$		,,
,, ,, ...	2	6	..	Broke	,,
The other half of same rail	1	5	$\frac{7}{8}$		84
,, ,, ...	2	6	$1\frac{7}{8}$		,,
,, ,, ...	3	7	3		,,
Became twisted and could not be	4	8	$4\frac{1}{8}$		,,
properly tested further	5	9	$4\frac{1}{2}$	Broke	,,

Table to the Appendix—*continued.*

	No. of blows.	Height of fall of the ball in feet.	Permanent deflection.	Broke.	Temperature. Deg. Fahr.
Aberdare rail No. 4. 21 ft. long ..	1	5	..	Broke	35
The one half of same rail	1	5	..	do.	,,
The other half of same rail	1	5	$\frac{3}{4}$		84
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{7}{8}$		,,
,, ,, ...	4	8	$3\frac{7}{8}$		,,
Became twisted and could not be tried	5	9	$4\frac{3}{4}$		,,
further	6	10	$6\frac{3}{4}$	Broke	,,
Aberdare rail No. 5. 21 ft.	1	5	$\frac{1}{2}$		35
,, ,, ...	2	6	1		,,
,, ,, ...	3	7	$1\frac{1}{4}$		,,
,, ,, ...	4	8	$2\frac{1}{2}$		,,
,, ,, ...	5	9	$3\frac{3}{8}$		,,
,, ,, ...	6	10	..	Broke	,,
One half of the same rail	1	5	$\frac{3}{4}$		10
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	..	Broke	,,
The other half of same rail	1	5	1		84
,, ,, ...	2	6	2		,,
,, ,, ...	3	7	3		,,
,, ,, ...	4	8	$4\frac{1}{2}$		,,
,, ,, ...	5	9	6		,,
,, ,, ...	6	10	$7\frac{1}{2}$		,,
,, ,, ...	7	11	..	Broke	,,
Aberdare rail No. 6. 21 ft.	1	5	$\frac{3}{4}$		10
,, ,, ...	2	6	..	Broke	,,
The one half of same rail	1	5	..	do.	,,
The other half of same rail	1	5	$\frac{3}{4}$		84
,, ,, ...	2	6	$1\frac{7}{8}$		,,
,, ,, ...	3	7	$2\frac{7}{8}$		,,
,, ,, ...	4	8	4		,,
,, ,, ...	5	9	$5\frac{1}{2}$		,,
,, ,, ...	6	10	$7\frac{1}{2}$		,,
,, ,, ...	7	11	..	Broke	,,
Aberdare rail No. 7. 21 ft.	1	5	..	Broke	10
The one half of same rail	1	5	..	do.	,,
The other half of same rail	1	5	1		84
,, ,, ...	2	6	$1\frac{7}{8}$		,,
,, ,, ...	3	7	3		,,
,, ,, ...	4	8	$4\frac{1}{2}$		,,
,, ,, ...	5	9	..	Broke	,,

REMARKS.—The rails were supported by two granite blocks, 4 feet apart, which rested on a planed granite-rock. The weight of the ball was 9 cwt., and the permanent deflection was measured between a distance of 4 feet.

Table to the Appendix—*continued.*

	No. of blows.	Height of fall of the ball in feet.	Permanent deflection.	Broke.	Temperature. Deg. Fahr.
Creusot rail No. 1. 21 ft.	1	5	½		35
,, ,, ...	2	6	1		,,
,, ,, ...	3	7	1⅝		,,
,, ,, ...	4	8	..	Broke	,,
The one half of same rail	1	5	¾		10
,, ,, ...	2	6	1⅞		,,
,, ,, ...	3	7	2½		,,
,, ,, ...	4	8	..	Broke	,,
The other half of same rail	1	5	¾		84
,, ,, ...	2	6	1¾		,,
,, ,, ...	3	7	2½		,,
,, ,, ...	4	8	3½		,,
,, ,, ...	5	9	4½		,,
,, ,, ...	6	10	..	Broke	,,
Creusot rail No. 2. 21 ft.	1	5	½		35
,, ,, ...	2	6	1		,,
,, ,, ...	3	7	..	Broke	,,
One half of the same rail	1	5	¾		10
,, ,, ...	2	6	..	Broke	,,
The other half of same rail	1	5	1		84
,, ,, ...	2	6	1½		,,
,, ,, ...	3	7	2½		,,
,, ,, ...	4	8	4		,,
,, ,, ...	5	9	..	Broke	,,
Creusot rail No. 3. 21 ft.	1	5	½		35
,, ,, ...	2	6	..	Broke	,,
One half of the same rail	1	5	¾		10
,, ,, ...	2	6	1¾		,,
,, ,, ...	3	7	..	Broke	,,
The other half of same rail	1	5	¾		84
,, ,, ...	2	6	1½		,,
,, ,, ...	3	7	2½		,,
,, ,, ...	4	8	3½		,,
,, ,, ...	5	9	..	Broke	,,
Creusot rail No. 4. 21 ft.	1	5	½		35
,, ,, ...	2	6	1		,,
,, ,, ...	3	7	1⅝		,,
,, ,, ...	4	8	2¾		,,
,, ,, ...	5	9	..	Broke	,,
One half of the same rail	1	5	¾		10
,, ,, ...	2	6	..	Broke	,,
The other half of same rail	1	5	¾		84
,, ,, ...	2	6	1¾		,,
,, ,, ...	3	7	2¾		,,
,, ,, ...	4	8	4		,,
,, ,, ...	5	9	4⅞		,,
,, ,, ...	6	10	..	Broke	,,

Table to the Appendix—*continued.*

	No. of blows.	Height of fall of the ball in feet.	Permanent deflection.	Broke.	Temperature. Deg. Fahr.
Creusot rail No. 5. 21 ft.	1	5	$\frac{3}{8}$		35
,, ,, ...	2	6	1		,,
,, ,, ...	3	7	$1\frac{3}{4}$		,,
,, ,, ...	4	8	..	Broke	,,
One half of the same rail	1	5	..	Broke	10
The other half of same rail	1	5	$\frac{7}{8}$		84
,, ,, ...	2	6	$1\frac{3}{4}$		,,
,, ,, ...	3	7	$2\frac{3}{4}$		,,
,, ,, ...	4	8	4		,,
,, ,, ...	5	9	..	Broke	,,
Belgian rail No. 1. 21 ft.	1	4	..	Broke	10
One half of the same rail	1	4	$\frac{3}{4}$		10
,, ,, ...	2	5	..	Broke	,,
The other half of same rail	1	4	1		84
,, ,, ...	2	5	$2\frac{1}{8}$		,,
,, ,, ...	3	6	$3\frac{1}{2}$		,,
,, ,, ...	4	7	..	Broke	,,
Belgian rail No. 2. 21 ft.	1	4	..	Broke	10
One half of the same rail	1	4	..	Broke	,,
The other half of same rail	1	4	$\frac{7}{8}$		84
,, ,, ...	2	5	2		,,
,, ,, ...	3	6	$3\frac{1}{8}$		,,
,, ,, ...	4	7	$4\frac{1}{2}$		,,
,, ,, ...	5	8	..	Broke	,,

INDEX.

INDEX.[1]

A.

B.

C.

[1] The Swedish characters Å and Ö should in strictness be placed at the end of the alphabet, but for the convenience of the English reader they are here placed under the corresponding unmodified letters: thus, Å will be found under A, and Ö under O.—*Translator.*

ercent

W. West, lith.

W. West lith.